Bulletin

of

The Geological Society of America

VOLUME 60 March 1949 NUMBER 3

CONTENTS

Leduc oil field, Alberta, Canada. By Theo. A. Link 381–402

Devonian-Mississippian formations of southeast Iowa. By Leo A. Thomas. 403–438

The system MgO-SiO_2-H_2O. By N. L. Bowen and O. F. Tuttle 439–460

Subsidence in the Long Beach Harbor area, California. By James Gilluly and U. S. Grant 461–530

Further studies in biogeochemistry. By Harry V. Warren and Robert E. Delavault 531–560

Subscription $10 per year.

Publication Office: Mt. Royal & Guilford Aves., Baltimore 2, Md.

Communications for publication should be addressed to The Geological Society of America, Dr. H. B. Aldrich, Secretary, 419 West 117th Street, New York 27, N. Y.

NOTICE.—Four weeks notice of change of address is necessary. In accordance with the rules established by the Council, claims for non-receipt of the preceding number of the Bulletin must be sent to the Secretary of the Society within three months of the date of the receipt of this number in order to be filled gratis.

Entered as second-class matter in the Post-Office at Baltimore, Md., under the Act of Congress of July 16, 1894.

Accepted for mailing at special rate of postage provided for in Section 1103 Act of October 3, 1917, authorized on July 8, 1918.

PAPERS IN PRESS FOR FORTHCOMING ISSUES

DISTRIBUTION OF MOUNTAIN BUILDING IN GEOLOGIC TIME. By James Gilluly

KARROO DOLERITES OF THE UNION OF SOUTH AFRICA. By Frederick Walker and Arie Poldervaart

STRUCTURE OF THE NORTHERN MUDDY MOUNTAIN AREA, NEVADA. By Chester R. Longwell
This paper contains a colored geologic map of the area (20 by 18 inches). Scale 1 inch = 1 mile. Separate copies of the map (unfolded, in tubes) may be purchased. Price 35 cents apiece. Please send remittance with order.

LOWER MIDDLE ORDOVICIAN OF SOUTH-CENTRAL PENNSYLVANIA. By L. C. Craig

SUBSURFACE CONSTITUTION OF BIKINI ATOLL AS INDICATED BY A SEISMIC REFRACTION SURVEY. By M. B. Dobrin, Beauregard Perkins, and B. L. Snavely

OBSERVATIONS IN SOME YELLOWSTONE GEYSERS. By F. Donald Bloss and Tom. F. W. Barth

PORTION OF THE SAN ANDREAS RIFT IN SOUTHERN CALIFORNIA. By Robert E. Wallace
This paper contains a colored geologic map of the area (11 by 43 inches) including portions of the following quadrangles: Hughes Lake, Lake, Del Sur, Lancaster, Bouquet Reservoir, Red River, Palmdale. Scale 2 inches = 1 mile. Separate copies of the map (unfolded, in tubes) may be purchased. Price 50 cents apiece. Please send remittance with order.

CANADA

DEPARTMENT OF MINES AND RES

MINES AND GEOLOGY BRANCH

BUREAU OF GEOLOGY AND TOPOGRAP

WITH ADDITIONS BY THE AUTH

MARCH 1948

LEGEND

CENOZOIC

TERTIARY

4 — *PASKAPOO FORMATION: light grey sandstone, greenish and grey, in part carbonaceous, shale*

MESOZOIC

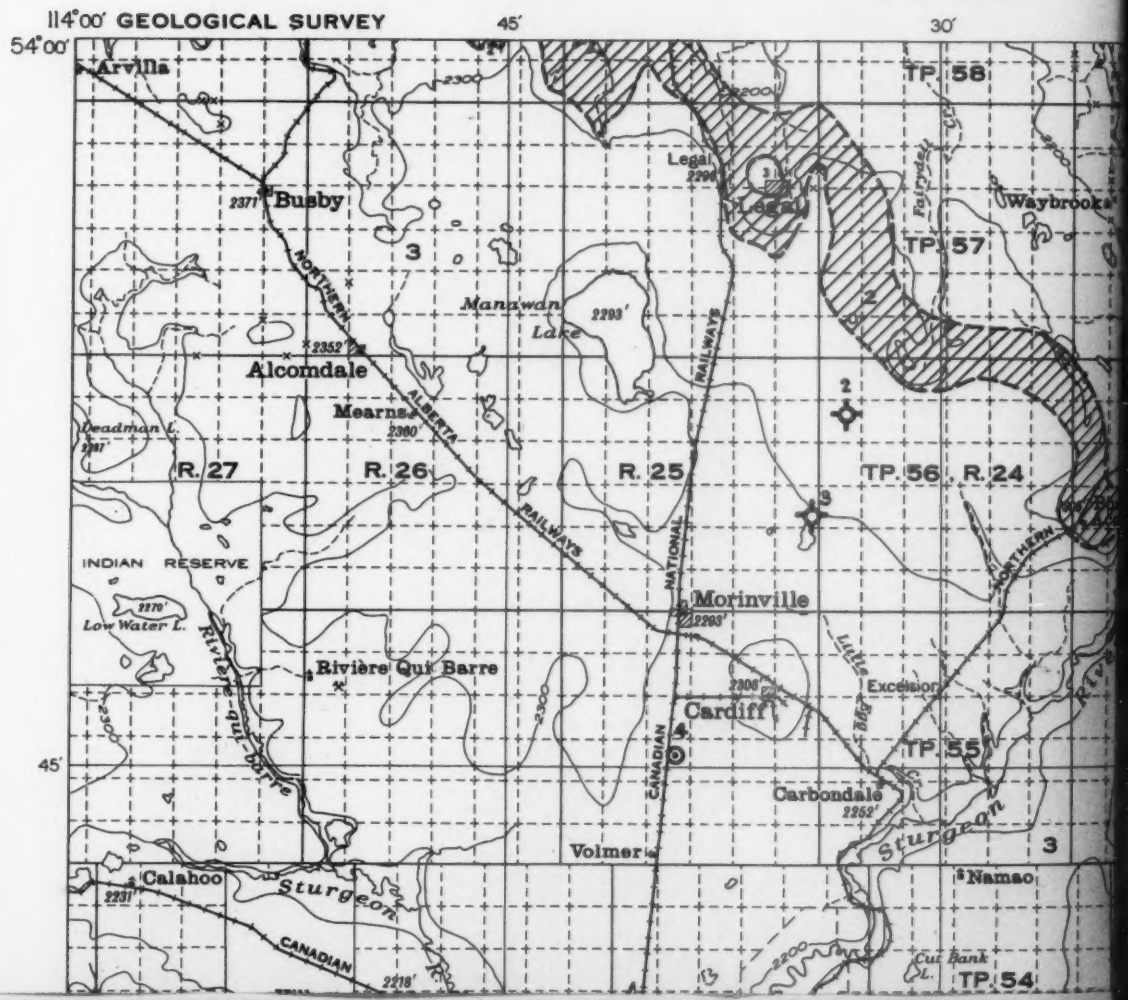
CRETACEOUS

UPPER CRETACEOUS

3 — *EDMONTON FORMATION: argillaceous sandstone, dark, bentonitic shale; coal seams*

2 — *BEARPAW FORMATION: light coloured clay, thin beds of sandstone; ironstone nodules; in places conglomerate with black quartzite and chert pebbles*

1 — *PALE AND VARIEGATED BEDS: light and dark coloured shale, bentonitic arenaceous shale and sandstone; coal seams*



CANADA

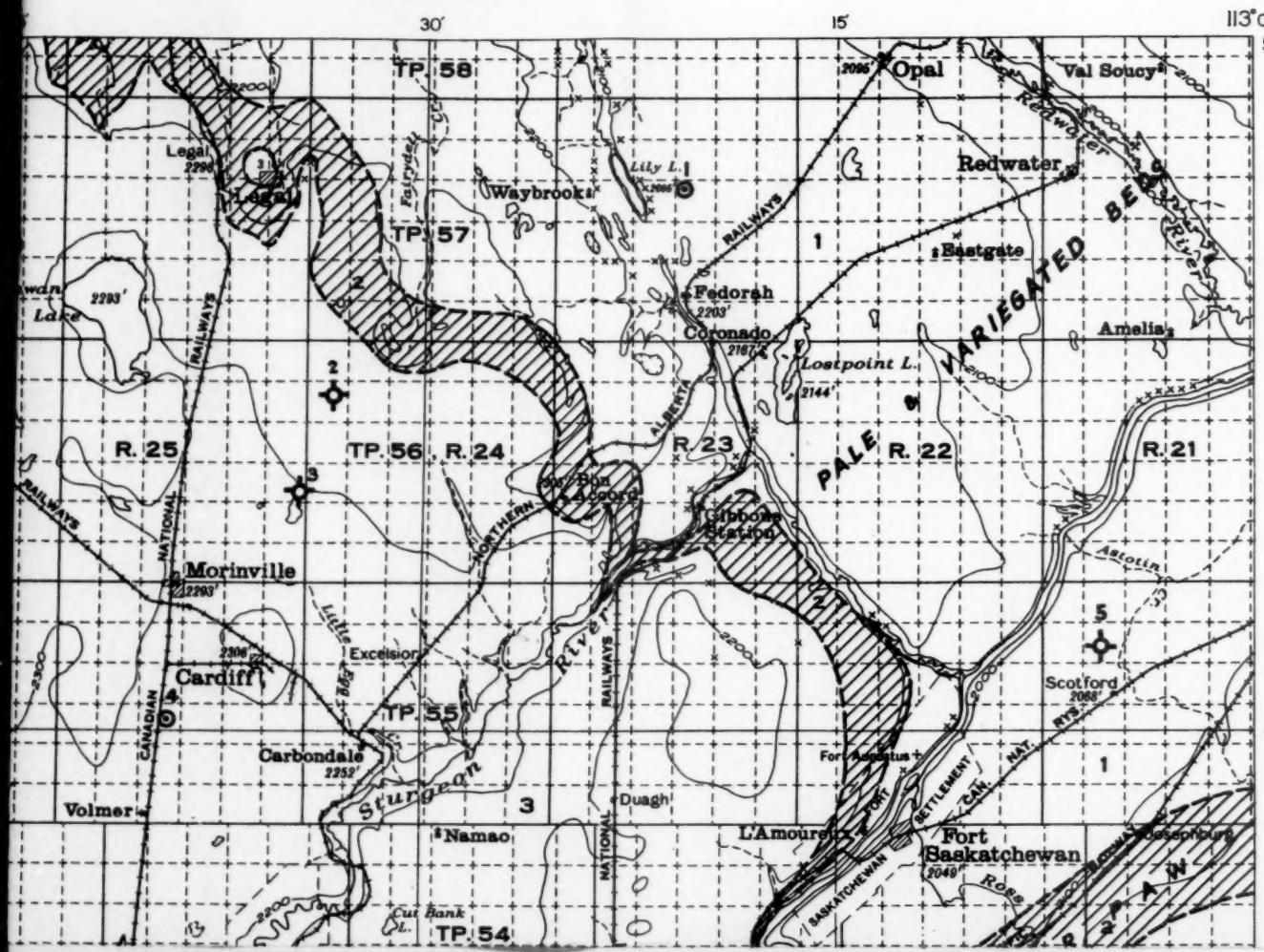
DEPARTMENT OF MINES AND RESOURCES

MINES AND GEOLOGY BRANCH

BUREAU OF GEOLOGY AND TOPOGRAPHY

WITH ADDITIONS BY THE AUTHOR

MARCH 1948



LIST OF WILDCAT WELLS

1. *Imp. Fedorah*
2. *Imp. Morinville*
3. *American Const.*
4. *Imp. Volmer*
5. *Ft. August.*

Geological boundary (approximate)
Rock outcrop
Coal mine

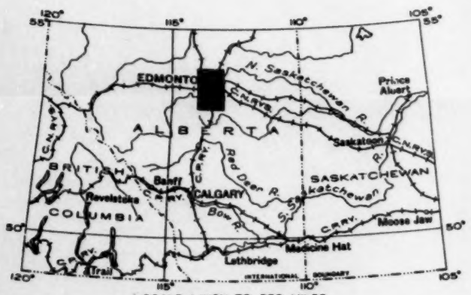
Post Office
Railway Station and Post Office
Township boundary
Section line
Land Settlement boundary
Indian Reserve boundary
Intermittent lake and stream
Contours (interval 100 feet)
Depression contour
Height in feet above Mean sea-level
Producing Oil Well
Drilling Well
Abandoned Well
Oil Pipe Line to R.R

Geology by R. L. Rutherford, 1935 and 1936.

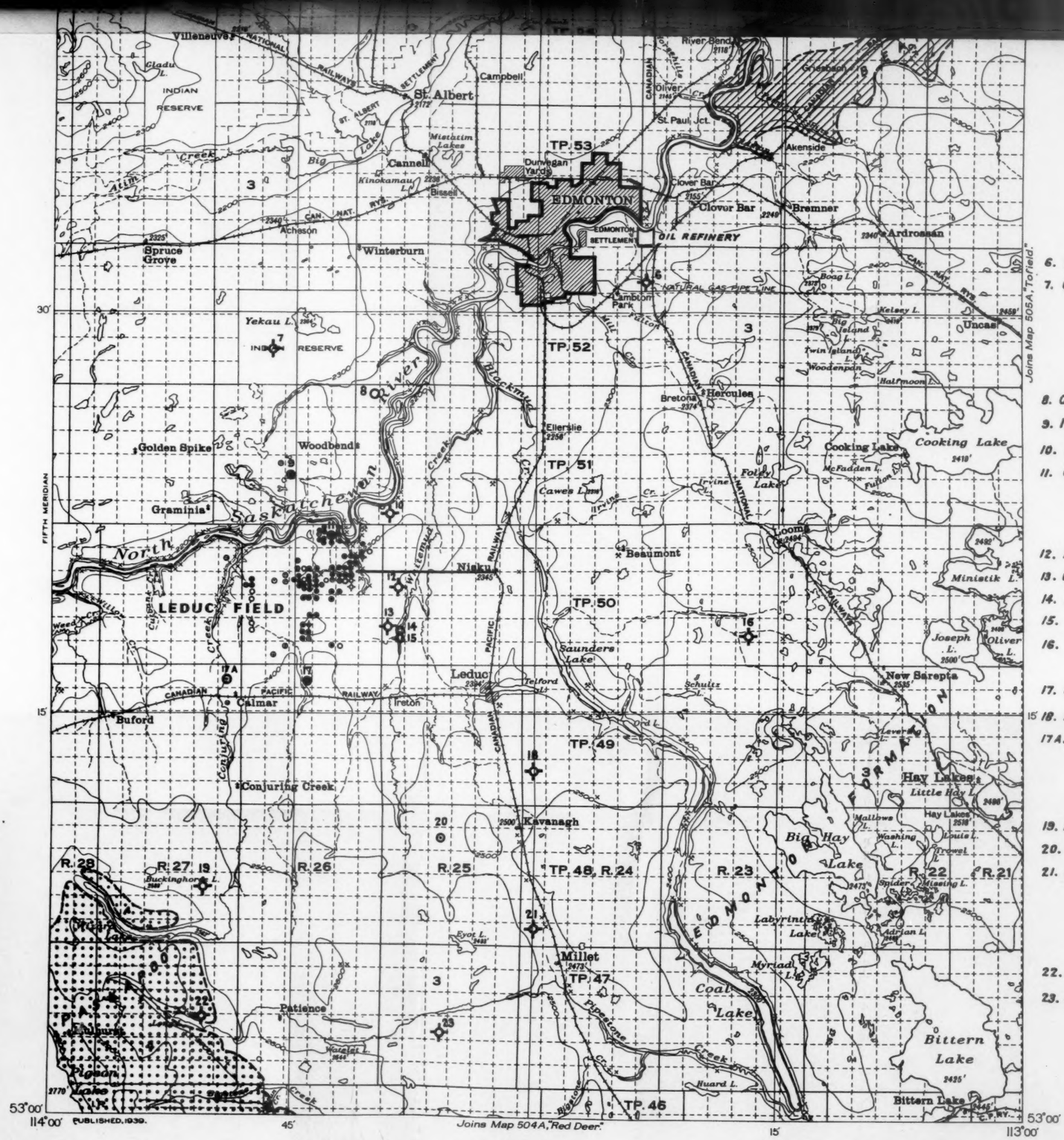
Base-map prepared by the Topographical Survey, 1938, from Federal Government maps published in 1915, 1920, and 1921. Cartography by the Drafting and Reproducing Division, 1939.

DIAGRAM OF TOWNSHIP SHOWING NUMBERING OF SECTIONS

31	32	33	34	35	36
30	29	28	27	26	25
19	20	21	22	23	24
18	17	16	15	14	13
7	8	9	10	11	12
6	5	4	3	2	1



SCALE, 1 INCH TO 200 MILES



6. Fairholme
7. Gulf Stoney Plain
8. Cons. Homestead
9. Imp. Woodband
10. E. Leduc 2
11. Globe Led. W. 2
12. Homestead Yaremko
13. Okalta Leduc 1
14. Leduc Cont. 4
15. " " 3
16. Imp. Looma
17. Okalta Leduc 2
18. New Ranchmens L. 1
17A. Tex. McC. Calmar 1.
19. McC.-Front. 14-14
20. Imp. Eyot.
21. Millet Leduc 1
22. Mutual Dev. 1
23. Ashley-McC.-Pipestone Cr.

PUBLISHED, 1939.

MAP 506A

EDMONTON

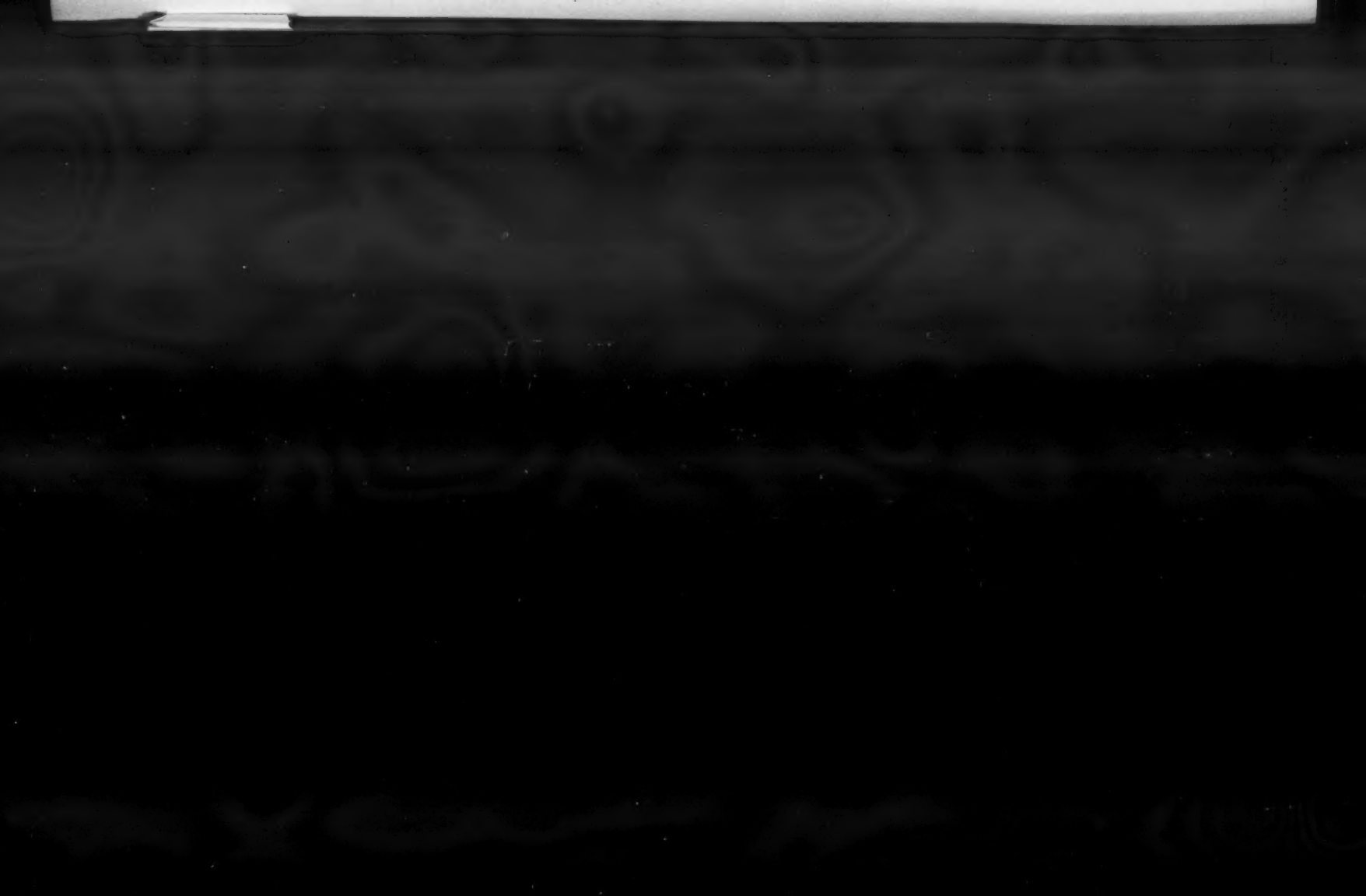
ALBERTA

Scale, $\frac{1}{253440}$ or 1 Inch to 4 Miles

Miles 0 4 8 12

Approximate magnetic declination, 24°30' to 26° East.

MAP OF EDMONTON, ALBERTA AND VICINITY



BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 60, PP. 381-402, 16 FIGS., 3 PLS. MARCH 1949

LEDUC OIL FIELD, ALBERTA, CANADA

(An Example of Transgressive and Regressive Bioherm Growth)

BY THEO. A. LINK

CONTENTS

	Page
Abstract	382
Introduction	382
Acknowledgments	382
Location and geologic setting	382
Stratigraphy	383
Structure	387
Origin of oil	388
Transgressive and regressive bioherm development (a suggested hypothesis)	391
Transgressive type of bioherm	391
Norman Wells (reef) bioherm	392
Regressive type of bioherm	393
Variation of sea-bottom slope	394
Suggested bioherm or reef history for Leduc area	399
Application to West-Texas-New Mexico Permian bioherms	399
Summary	400
References cited	400

ILLUSTRATIONS

Figure	Page
1.—Map of oil and gas fields of Alberta	383
2.—Map of tectonic features of Western Canada	384
3.—Type log, Leduc area, Alberta	384
4.—Leduc area geologic structure-contour map, top of Lower Cretaceous	385
5.—Leduc area geologic structure-contour map, top of D-2 zone	386
6.—Leduc area geologic structure-contour map, top of D-3 zone	387
7.—Cross section, Leduc oil field	388
8.—Reef development during transgression of sea	392
9.—Longitudinal cross section of Norman Wells	393
10.—Transverse cross section of Norman Wells	394
11.—Reef development during regression of the sea	395
12.—Idealized map showing configuration of basin over which sea advanced	395
13.—Ideal diagram showing concentration of transgressive type of bioherm on steeper slope during advance of the sea	396
14.—Ideal section showing development of regressive bioherms (reefs) concentrated on steeper slope	397
15.—Ideal section showing bioherms (reefs) deposited on steeper slope during transgression of sea and during regression of sea	397
16.—Hypothetical development of D-3 bioherm (reef)	398

Plate — Facing page
1.—Map of Edmonton, Alberta, and vicinity 381
2.—Photographs of cores 402
3.—Photograph of Imperial Leduc No. 3 blowing into production 403

ABSTRACT

On February 13, 1947, a commercial oil pool, which may prove to be the largest in Canada, was discovered near the village of Leduc, Alberta. Production was found in two limestone-dolomite zones of Late Devonian age. Although structural relief is indicated, oil and gas accumulation is apparently due primarily to a stratigraphic trap created by coral-reef or bioherm development.

The ultimate oil reserves, areal extent, structural and stratigraphic configuration, and other data must await further development of the field.

The shallower discovery zone is an example of a "regressive type" of bioherm (coral reef), while the lower, but more prolific, zone is a "transgressive type". These two types of bioherm development are discussed. Application of these principles to the Permian reef problem of West Texas and New Mexico is suggested.

INTRODUCTION

On February 13, 1947, Imperial Oil Limited of Canada discovered the Leduc oil field in Alberta, which promises to develop into the largest in Canada.[1] The discovery well was located on the basis of a seismic-reflection survey by the Heiland Exploration Company of Canada. This find culminated an intensive and long search throughout the sedimentary basin area of Western Canada from the International boundary to the Arctic Ocean, and from the pre-Cambrian Shield to the Rocky Mountains and justified the belief of many Alberta geologists (Alberta Society of Petroleum Geologists, 1941, p. 1452) that the Upper Devonian had promising oil possibilities:

"However, great interest attaches to the Devonian, particularly the Upper Devonian, since it has a fairly widespread petroliferous or bituminous character in outcrops and yields commercial production at Fort Norman in the Mackenzie River district; some slight production at Moose Mountain; showings at Clearwater and Prairie Creek in the southern foothills; and at Steveville on a branch of the Sweetgrass arch".

ACKNOWLEDGMENTS

Dr. O. B. Hopkins, Vice-President of Imperial Oil Limited, Toronto, Ontario, kindly granted permission to publish this paper. For the facts and data that form the basis for interpretation of the Leduc field as here presented, the author acknowledges with thanks the co-operation of his colleagues on the geological, geophysical, and engineering staffs of Imperial Oil Limited in Calgary, Alberta. In particular, for detailed descriptions of formations he is indebted to Mr. J. B. Newland; and, for photographs of drill cores, to Mr. D. B. Layer. The cross sections of the Norman Wells pool are based upon data compiled by Mr. O. D. Boggs.

LOCATION AND GEOLOGIC SETTING

The Leduc oil field is in T. 50, R. 26 W. (of the 4th meridian), approximately 16 miles southwest of Edmonton (Fig. 1). It is situated in the Great Plains area of

[1] The Leduc field is today regarded as the largest in Canada, but may be surpassed by the more recently discovered Redwater pool 37 miles northeast of Edmonton (December 1948).

Western Canada, where the surface bedrock is Upper Cretaceous, dipping gently southwestwardly from the distant pre-Cambrian Shield into the deep Alberta syncline (Fig. 2).

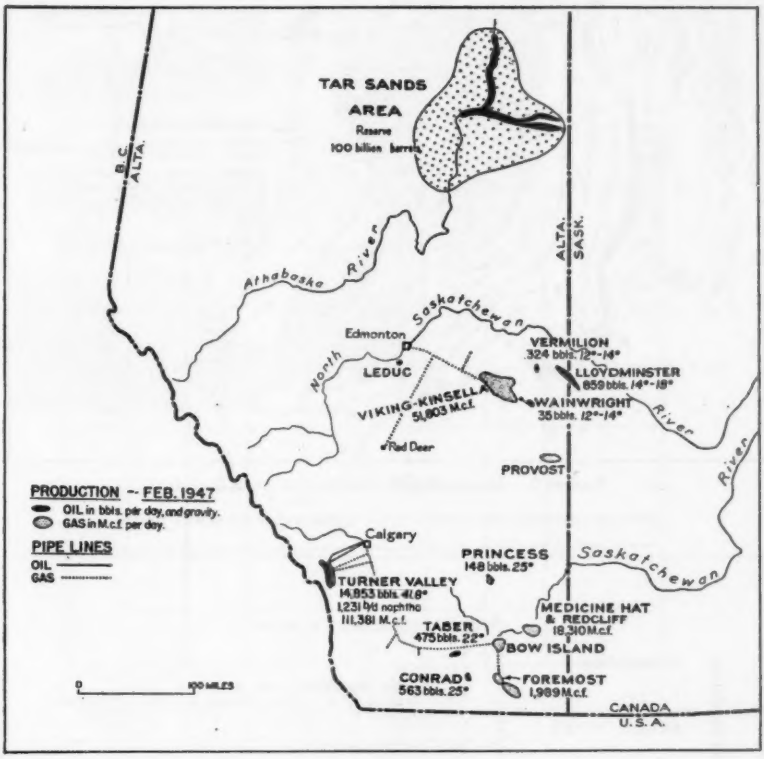


FIGURE 1.—*Map of oil and gas fields of Alberta*

Showing location of Leduc oil field with respect to other oil and gas fields and the Tar Sands area

STRATIGRAPHY

The surface bedrock in the Leduc area is the Edmonton formation, from which coal is mined in and near the city of Edmonton (Pl. 1). Figure 3, an abridged geologic column for the Leduc area, was compiled from well data. The Edmonton and Belly River beds are grouped together since the interfingering Bearpaw shale marine tongue was not differentiated in studying the well cuttings.

The Viking sand, near the base of the Upper Cretaceous, showed gas in many holes. In the Lower Cretaceous section several sandstones have been encountered, but no commercial production has been obtained from them.[2] At Imperial Leduc No. 1 a

[2] Commercial production from the Lower Cretaceous has been developed in the northern part and extension of the Leduc field (December 1948).

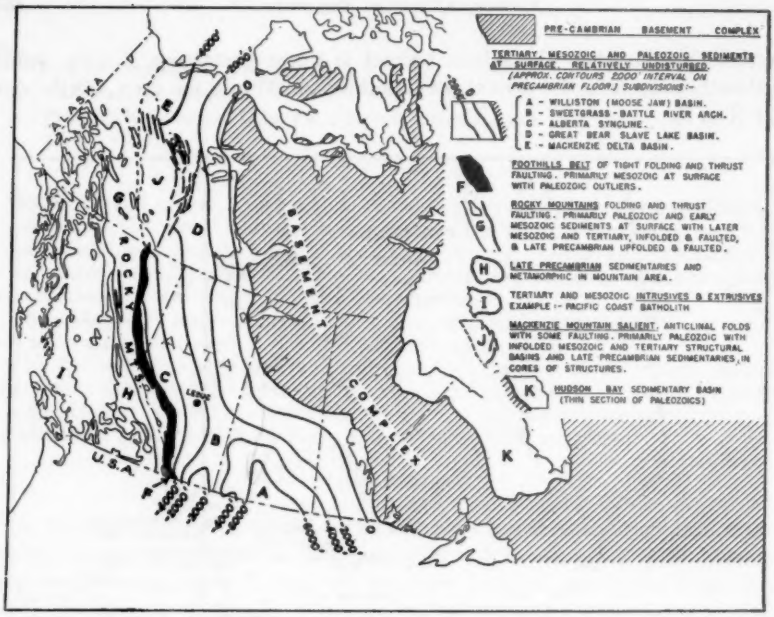

PRE-CAMBRIAN BASEMENT COMPLEX
TERTIARY, MESOZOIC AND PALEOZOIC SEDIMENTS AT SURFACE, RELATIVELY UNDISTURBED. (APPROX. CONTOURS 2000' INTERVAL ON PRECAMBRIAN FLOOR.) SUBDIVISIONS:-
A - WILLISTON (MOOSE JAW) BASIN.
B - SWEETGRASS - BATTLE RIVER ARCH.
C - ALBERTA SYNCLINE.
D - GREAT BEAR SLAVE LAKE BASIN.
E - MACKENZIE DELTA BASIN.
FOOTHILLS BELT OF TIGHT FOLDING AND THRUST FAULTING. PRIMARILY MESOZOIC AT SURFACE WITH PALEOZOIC OUTLIERS.
ROCKY MOUNTAINS FOLDING AND THRUST FAULTING. PRIMARILY PALEOZOIC AND EARLY MESOZOIC SEDIMENTS AT SURFACE WITH LATER MESOZOIC AND TERTIARY, INFOLDED & FAULTED, & LATE PRECAMBRIAN UPFOLDED & FAULTED.
LATE PRECAMBRIAN SEDIMENTARIES AND METAMORPHIC IN MOUNTAIN AREA.
TERTIARY AND MESOZOIC INTRUSIVES & EXTRUSIVES EXAMPLE :- PACIFIC COAST BATHOLITH
MACKENZIE MOUNTAIN SALIENT. ANTICLINAL FOLDS WITH SOME FAULTING. PRIMARILY PALEOZOIC WITH INFOLDED MESOZOIC AND TERTIARY STRUCTURAL BASINS AND LATE PRECAMBRIAN SEDIMENTARIES IN CORES OF STRUCTURES.
HUDSON BAY SEDIMENTARY BASIN (THIN SECTION OF PALEOZOICS)
ALASKA
ROCKY MTS.
BASEMENT
COMPLEX
U.S.A.
LEDUC
A
B
C
D
E
F
G
H
I
J
K

FIGURE 2.—*Map of tectonic features of Western Canada*

Showing location of Leduc oil field on west-dipping flank of the Alberta syncline

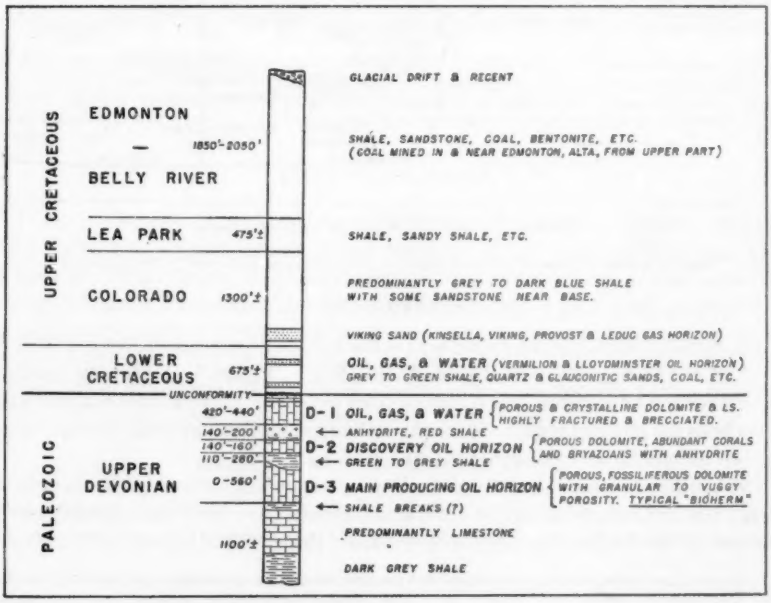

GLACIAL DRIFT & RECENT
UPPER CRETACEOUS
EDMONTON
1850'-2050'
SHALE, SANDSTONE, COAL, BENTONITE, ETC. (COAL MINED IN & NEAR EDMONTON, ALTA, FROM UPPER PART)
BELLY RIVER
LEA PARK 475'±
SHALE, SANDY SHALE, ETC.
COLORADO 1300'±
PREDOMINANTLY GREY TO DARK BLUE SHALE WITH SOME SANDSTONE NEAR BASE.
VIKING SAND (KINSELLA, VIKING, PROVOST & LEDUC GAS HORIZON)
LOWER CRETACEOUS 675'±
OIL, GAS, & WATER (VERMILION & LLOYDMINSTER OIL HORIZON)
GREY TO GREEN SHALE, QUARTZ & GLAUCONITIC SANDS, COAL, ETC.
UNCONFORMITY
PALEOZOIC
420'-440'
140'-200'
140'-160'
110'-280'
UPPER DEVONIAN
0-560'
D-1 OIL, GAS, & WATER
POROUS & CRYSTALLINE DOLOMITE & LS. HIGHLY FRACTURED & BRECCIATED.
ANHYDRITE, RED SHALE
D-2 DISCOVERY OIL HORIZON
POROUS DOLOMITE, ABUNDANT CORALS AND BRYAZOANS WITH ANHYDRITE
GREEN TO GREY SHALE
D-3 MAIN PRODUCING OIL HORIZON
POROUS, FOSSILIFEROUS DOLOMITE WITH GRANULAR TO VUGGY POROSITY. TYPICAL "BIOHERM"
SHALE BREAKS (?)
1100'±
PREDOMINANTLY LIMESTONE
DARK GREY SHALE

FIGURE 3.—*Type log, Leduc area, Alberta*

sand in the upper part of the Lower Cretaceous yielded a high-quality oil, with gas and some water on a drill-stem test, but this proved to be noncommercial. This same zone produced water downdip at Imperial Leduc No. 2.

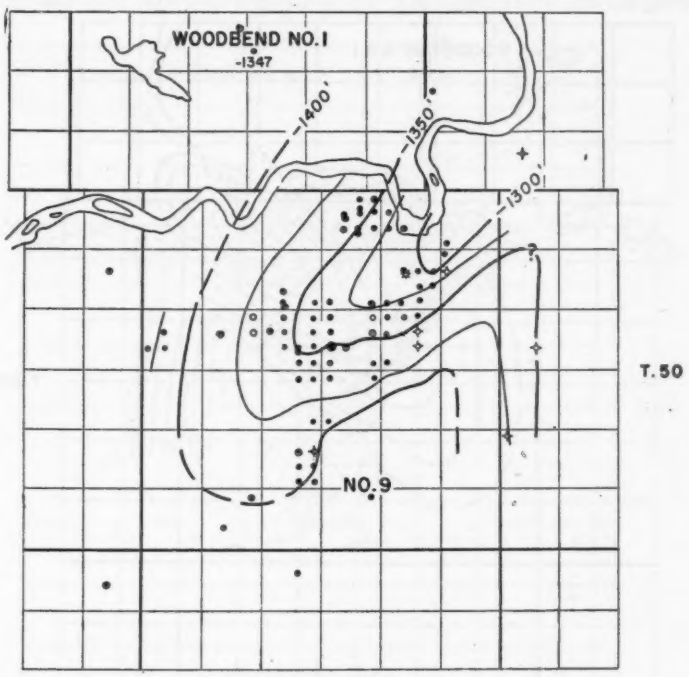


FIGURE 4.—*Leduc area geologic structure-contour map, top of Lower Cretaceous*

Contour interval, 25 feet

A major unconformity at the base of the Lower Cretaceous eliminates Jurassic, Triassic, Permian, and Carboniferous rocks. The Madison (Rundle) limestone, which is the main pay of the Turner Valley field, is not represented at Leduc. Thus, the drill passes directly from Lower Cretaceous into Upper Devonian rocks, the uppermost member which is termed the D-1 zone in the Leduc area (Fig. 3). This zone consists of dolomite and limestone locally brecciated and porous. Gas, oil, and water have been encountered in practically all holes drilled through this zone, but the D-1 zone has no commercial production to date. Below the D-1 zone lies anhydrite, at the base of which is a red shale that is an excellent marker for subsurface correlation. The combined thickness of the anhydrite and red shale is 140–200 feet.

The D-2 zone, discovery horizon in the Leduc field, consists of dense, granular dolomite with intergranular and vuggy porosity, abundant corals, bryozoans, and anhydrite infilling some of the pores. There is also some red shale and calcareous

dolomite near the base. Porosity in this zone is not uniform throughout the field, but to date many good commercial producers have been completed in the discovery zone, which is 140–160 feet thick.

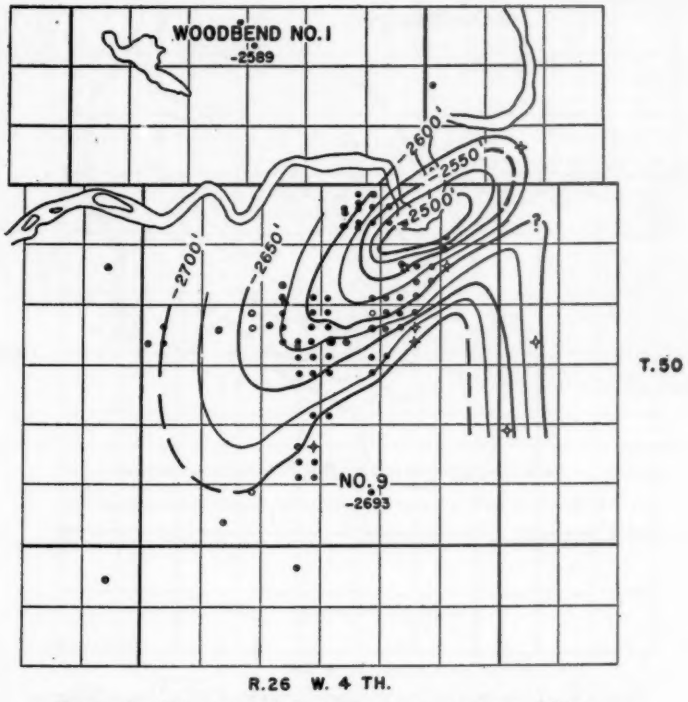


FIGURE 5.—*Leduc area geologic structure-contour map, top of D-2 zone*

Contour interval, 25 feet

A gray to drab-green shale 110 to 280 feet thick underlies the D-2 zone. Locally i contains fossils, silt, and some dolomite. It is an excellent impervious cap surrounding the underlying porous D-3 zone.

The D-3 or main producing zone ranges in thickness from zero to 560 feet (Fig. 3). It is believed to be a typical reef or bioherm which grew during one of the advances of the Late Devonian sea, thus causing it to be enveloped by shale. The D-3 zone also consists of dense though vuggy dolomite and contains abundant corals and bryozoans, and some brachiopods and other fossils. Cores indicate considerable fracturing and loaclly high porosity and permeability. (*See* Plate 2.) One core (Pl. 2, fig. 5) is from the gas cap at Leduc No. 20. Some of the large pores in the gas cap are lined with dolomite crystals and black shiny pyrobitumen. The pyrobitumen is absent in cores from the oil-saturated level. Anhydrite is negligible in the D-3 zone, and no red color has been detected as is the case in the D-2 zone.

Only one well has been drilled through the D-3 zone, and data representing lower zones are based upon this location, Central Leduc No. 1 (also known as B. A. Pyrcz No. 1). The D-3 zone rests upon a thin shale, which overlies 1100 feet of limestone; the latter rests upon dark-gray shales (Fig. 3). The Upper Devonian, the producing

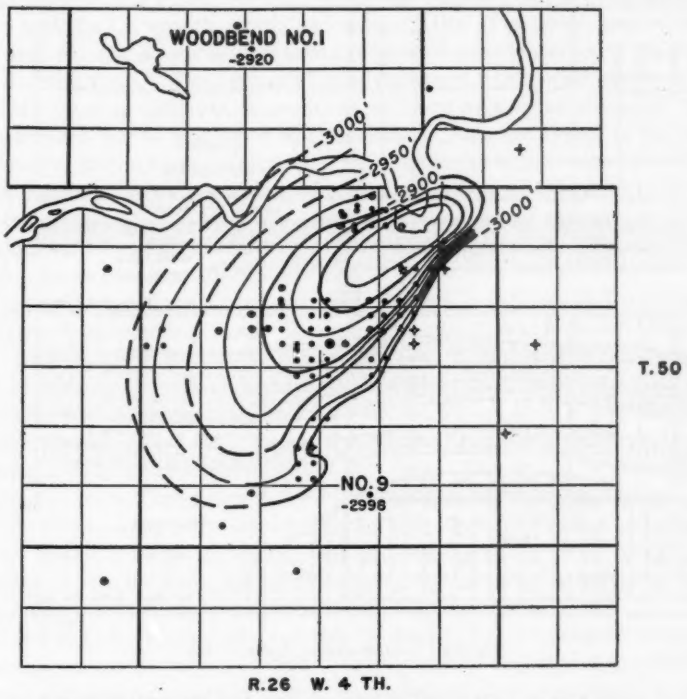


FIGURE 6.—*Leduc area geologic structure-contour map, top of D-3 zone*

Contour interval, 25 feet

zone in the Leduc area, is regarded in the Mackenzie River area as the equivalent of the Fort Creek shale, which includes the Norman Wells reef pool and is correlated with the Genesee-Portage of New York.

STRUCTURE

Present evidence indicates a strong structural nose, pointing S. 30°-50° W. into the Alberta syncline, almost at right angles to the regional dip. This structure may be the result of tectonic forces, differential compaction, or a combination of both. The structure-contour map (Fig. 4) constructed on top of the Lower Cretaceous, indicates this "nose". Additional drilling may show closure on the northeast side. The structure-contour map constructed on the top of the D-2 zone (below the unconformity) (Fig. 5) suggests a change of structure at the unconformity. The dips are definitely

steeper below than above the unconformity, thus intensifying possibility of closure on the northeast.

A contour map on top of the D-3 producing zone (Fig. 6) reveals a possible draping of later sediments over the D-3 reef or "bioherm". A considerable closure on the

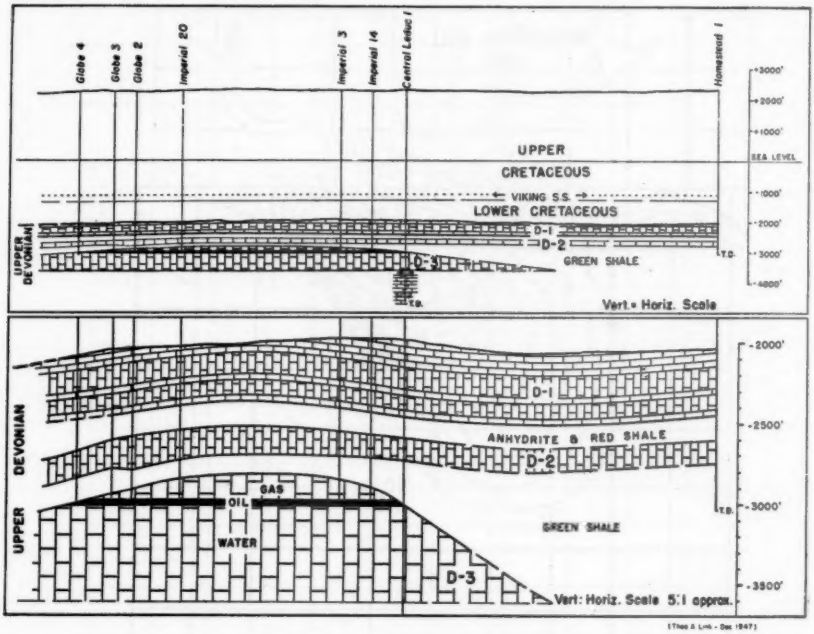


FIGURE 7.—*Cross section, Leduc oil field*

northeast side is almost certain at this horizon, and dips are steeper than on the overlying beds. Whether these features were produced by compaction of the later sediments over the D-3 reef or by tectonic arching, adjustment faulting, or combinations of these is unknown. The current structure-contour maps will need revision as new data become available. However, Figure 7 (top) indicates that oil would have accumulated in the D-3 zone bioherm reservoir without any subsequent folding. This cross section (to true vertical scale) shows the thickening of the green shale above the D-3 zone and thus indicates that Figure 6 is not a true structural interpretation, but a combination of structure and top-of-reef or bioherm configuration. Thus the structure is a stratigraphic trap. Also, the D-3 zone is not present at Homestead No. 1 at the extreme east. The true-scale cross section (Fig. 7, top) emphasizes the very gentle dip of the bioherm and the very limited zone of oil and gas accumulation near its top.

ORIGIN OF THE OIL

Using present data, possibly 60 per cent of the petroleum geologists would consider the surrounding shale and the underlying sediments as the source rock of the oil

accumulated at Leduc. Possibly 10 per cent might suggest that the overlying Cretaceous sediments were the source rock and that oil migrated from the Cretaceous through the unconformity into the Devonian. The remaining 30 per cent (Link, 1947) would probably favor the idea that the oil was not only stored in the bioherm but was also generated within the reef. When one considers that in bioherms conditions are ideal for the growth, death, and accumulation of countless generations of unnumbered organisms, why is it necessary to look for outside sources to explain the oil found within them? The concept of an environment where organisms would die because of unusual or catastrophic conditions, and thus wipe out an ecological assemblage to account for the generation of hydrocarbons, does not appeal to the writer nearly so much as the concept of an environment conducive to the natural growth of a fauna and/or flora, so that generation after generation would live and die by natural causes and accumulate almost *in situ*. Space does not permit enlargement on this subject, but very sound arguments can be marshalled in favor of the indigenous theory of origin as far as bioherms are concerned.

A recent article in Science News Letter (Oct. 30, 1948, p. 281) reports the findings of Prof. Werner Bergmann as follows: "It is the tiny animals that form coral reefs that are manufacturing the petroleum drop by drop. . . . Stony coral, he said, contains minute amounts of a wax-like substance which apparently becomes entrapped in the ever-growing reefs." In Science (Nov. 15, 1940, vol. 92, no. 2394, p. 452–453) under the caption *Coral-reefs and the formation of petroleum*, Professor Bergmann submitted a scientific discussion of his findings as of that date. This should be of interest to geologists who are pondering over that subject, and Professor Bergmann's conclusions add weight to the conception of coral reefs being both the original source and reservoir rock. Obviously subsequent folding, faulting, and fracturing could cause loss of accumulations from the ancient reefs or bioherms into other suitable reservoirs, should a pressure gradient exist between the reef and the other medium.

Coral-reef or bioherm reservoirs can best be described as a homogeneous mass of heterogeneous porosity which confounds the mathematical approach of the petroleum engineer to calculate their gas and oil reserves, and which likewise baffles the geologist as to size and configuration since no two bioherm reservoirs are identical because of their inherent complexity of accumulation and growth.

In addition to the irregular and unpredictable pore space within a bioherm it is commonly criss-crossed by minor adjustment faults and fractures that develop soon after the bioherm becomes large enough to begin settling and adjusting itself to its surroundings, and later to its overburden. These factors preclude an accurate estimate of the ultimate recoverable reserves of a coral-reef (bioherm) reservoir early in the history of such an oil pool, and rarely is the estimate as accurate as for sand-reservoir pools.

The porosity referred to, and shown in Plate 2, is regarded as of primary origin. The pores developed at the time of deposition and growth of the bioherm and are not regarded as "solution cavities". Some of the pores are regarded not as the hollow interior of corallites, but as remains of the original spaces between the individual lime-secreting organisms of the bioherm. Initial porosity of a bioherm can best be described by comparing it to a strawstack which has been compressed by an overburden. The individual hollow pieces of straw have their porisity, and the helter-skelter stack-

ing of the straw gives rise to even greater pore spaces. The same thing takes place in a coral reef which dies and is buried by later sediments. A sizable percentage of the original space between the variously shaped organisms is retained, producing the odd-shaped pores found in such a bioherm as the D-3 zone. Some of these can definitely be interpreted as the hollow insides of corallites, but the majority are the reduced spaces between the broken corals, algae, sponges, and bryozoans. This type of porosity is the most effective, because of continuity.

The presence of dolomite lining these pore spaces does not indicate that they are solution cavities. These dolomite or calcite linings are incipient secondary deposition or crystallization which, if continued, might eventually obliterate the porosity. However, such could not have taken place in the D-3 zone in the Leduc area because of its complete sealing-off by the surrounding and overlying green shale. On the other hand in the D-2 zone the bioherm (or biostrome) is overlain by anhydrite, evaporites, and red shale. During or after deposition of these evaporites, waters charged with anhydrite, calcite, and dolomite entered the D-2 zone and partially obliterated its primary porosity by secondary deposition of these minerals. Observation of cores indicates varying degrees of such obliteration of porosity. In some cases it is complete, and no production is obtained.

In the D-1 zone more damage to the original or primary porosity is in evidence, and, when this zone was at the surface, solution cavities developed, solution brecciation took place, and thus gave rise to very irregular and spotty porosity and oil, gas, and water accumulation within this zone. Since angular pieces of dark, oil-saturated dolomite are interbedded in the matrix, oil probably accumulated in the D-1 zone before brecciation and before the development of the Devonian-Cretaceous unconformity. It is therefore safe to conclude that the D-3 and D-2 accumulations of oil took place in the Devonian prior to the development of the unconformity and deposition of the Cretaceous. Consequently migration of oil from the Cretaceous through the unconformity seems highly improbable.

Accumulation of oil in the D-2 and D-1 zones is probably due to escape from the underlying D-3 zone via fractures, when these zones were near the surface (*i.e.*, before Cretaceous deposition). The fractures were subsequently closed during and after deposition of the Cretaceous and younger sediments.

The overworked term "solution cavities" is inherited from that phase of the West Texas Permian development when geologists, unaware of or unwilling to accept the coral-reef reservoir conception, were attempting to explain the porosity observed, or inferred from drilling results, by solution of limestone or dolomite.

Thus the author believes that the D-3 is the most prolific oil zone because of its primary or original porosity; the D-2 zone retains some of its original porosity, but secondary infilling by dolomite, calcite, and anhydrite is complete locally; and in the D-1 zone porosity is due to both primary and secondary solution, complicated by irregular solution brecciation as well as secondary and tertiary infilling by evaporites and silt. The oil in the D-1 zone is heavier and of inferior grade because it was at one time near the unconformity, and accumulation is irregular. All these factors point toward a definite Devonian origin of the oil.

Two very excellent contributions on the origin of oil in limestone or dolomite reservoirs are by Howard (1934) and Adams (1934).

TRANSGRESSIVE AND REGRESSIVE BIOHERM DEVELOPMENT (A SUGGESTED HYPOTHESIS)

The concept of transgressive and regressive deposition of sediments is a well-established principle of sedimentology and stratigraphy. The term "cyclic" and/or "rhythmic" deposition embody the same principles as does the biologic corollary of these, the "recurrence and migration of faunas". The author here applies these principles to the growth and migration of bioherms (reefs) and, from field evidence, differentiates between the "transgressive" and "regressive" types.

Most sessile organisms which form bioherms propagate by budding or stolonation as well as by sexual reproduction. Therefore, in an advancing sea, the bioherm-forming organisms must shift with the sea water by means of mobile, fertilized ovae, planulae, and ciliated larvae. Furthermore, the bioherm-forming organisms are not nearly so mobile and adaptable as the planktonic types, so that in rapid advance or retreat of an epicontinental sea they may not survive. However, each ciliated larva that anchors is a potential bioherm if it takes root in a favorable environment. Obviously, there must be considerable leeway in the environment for each type of bioherm-forming organism, be it temperature, depth below the surface of the water, circulating or stagnant water, or salinity (Vaughan, 1940). Otherwise the development of bioherms would not be so common or widespread as indicated in geologic history.

Because the so-called "coral reefs" consist of an assemblage of corals, bryozoans, sponges, algae, and other primitive sessile aquatic animals and plants, Cumings (1932) suggested the term "bioherm". In many of the present-day bioherms, corals and algae predominate, but those of past geologic ages varied considerably. The bioherms of the Permian of West Texas and New Mexico are largely algal remains, while those of the Devonian of Western Canada (Norman Wells and Leduc) are predominantly stromatoporoid corals and bryozoans.

TRANSGRESSIVE TYPE OF BIOHERM

Darwin (1897) maintained that coral reefs develop best during rise of the strand line; he presented detailed data to prove his point as far as atolls and fringing reefs were concerned. However, the records of geologic history indicate that reefs or bioherms developed during both advance and retreat of strand lines, and the Leduc area suggests this.

Figure 8[3] is an idealized hypothetical bioherm (R-1) growing upward because of a gradual rise in sea level, such as postulated by Darwin. Obviously, if the sea level were to remain stationary during a long period, the bioherm would grow laterally toward the open sea—all other factors remaining the same. If, however, submergence were more rapid than upward growth of the bioherm, the bioherm would be drowned, and, if no others had begun to develop in the shallower waters near by, this might well terminate bioherm growth in this area for this particular period. On the other hand, if minor bioherms had already begun to grow in the more favored shallow waters, some of these might grow into large bioherms. In Stage II is indicated such

[3] The vertical scale is, of necessity, greatly exaggerated in all the "idealized" diagrams submitted in this paper. The shapes of the bioherms are hypothetical.

a bioherm as R-2, which began its growth during the last stages of R-1, which is now dead and is being covered with shales and/or limestones. Continued submergence would eventually end the growth of bioherm R-2, and the successive bioherms indicated as R-3, R-4, and R-5 (Stage III) would produce a compound affair progressing shoreward, if submergence were fairly uniform. With continued submergence all

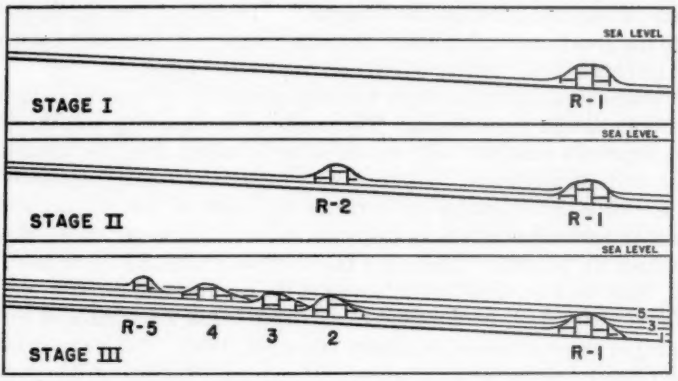


FIGURE 8.—*Reef development during transgression of sea*

R-1 to R-2, Rather sudden rise of strand line; R-2 to R-5, gradual and progressive rise of strand line.

these bioherms would eventually be covered by shale and/or limestone, and thus be sealed, so that any accumulation of oil, gas, and water would be in an isolated reservoir. The lower or D-3 producing horizon at Leduc is regarded as a reef or bioherm of this type, which grew vertically some 600 feet, owing to a progressive and gradual submergence of the area, but which was finally drowned. After complete delineation by drilling, this bioherm may prove to be an example of a semicircular, crescentic, or elongate fossil atoll.

NORMAN WELLS (REEF) BIOHERM

The Norman Wells oil pool in the Northwest Territories, Canada, is in a Devonian reef reservoir of approximately the same age as the Leduc D-3 zone, but it is almost entirely limestone. Figure 9 is a longitudinal cross section of this reef, which rests on Fort Creek shale and is surrounded and overlain by the Fort Creek. It is classified as a transgressive type, showing no evidence of difference in facies between the back-reef and fore-reef sediments (Lloyd, 1929). Anhydrite and other evaporites are essentially lacking within the normal Wells reef and are absent throughout the Mackenzie River basin in the surrounding and overlying shale. There is no counterpart to the D-2 zone in the Norman Wells area. A transverse section of the Norman Wells reef (Fig. 10) shows a striking similarity to the D-3 zone of the Leduc area. The total maximum thickness of the Norman Wells reef is 450–500 feet, which is also comparable to the maximum thickness of 560 feet in the D-3 zone at Leduc. The Fort Creek shale is a classic example of the black "pontic" or basin-facies type of

sediments, described for the Yates pool, Texas (Adams, 1930), and could readily be accepted as the source rock for the Norman Wells reef. When heated, the Fort Creek shales smoke, exude oil, and, in many instances, ignite. Throughout the Lower Mackenzie River area forest fires have burned many of the Fort Creek shale cliffs to a

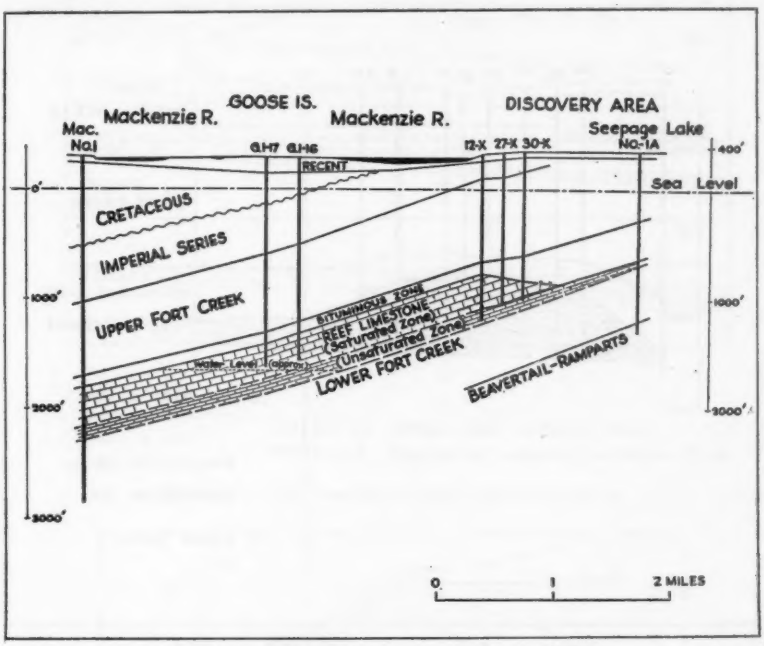


FIGURE 9.—*Longitudinal cross section of Norman Wells*

brilliant red. Might shale of this type be regarded as an example of a source rock that retained its hydrocarbons due to their inability to migrate freely through a fine-grained medium? Many experienced geologists have made such suggestions in recent years (Personal communication, Axel Olsson, Walter Link, and others), and the writer has referred to such oil as "still-born".

REGRESSIVE TYPE OF BIOHERM

Figure 11 shows how reef growth and basinward migration could take place. The first bioherm is indicated in Stage I as R-1. The back-reef or shoreward facies merges into the reef. (*See* King, 1942.) The immediate "fore-reef" and "basin" or "pontic" facies consists of gray to black, bedded limestone and shales merging with admixture of sands into the reef facies. With lowering of the strand line new reefs or bioherms develop seaward at favorable depths (R-2 in Stage II), while the emergent reef R-1 is at or above sea level and being destroyed. Solution brecciation would take place during this phase. If the withdrawal between Stage I and Stage II were sudden, a gap

could develop between reefs R-1 and R-2; but, if lowering were gradual but progressive, a continuous succession of reefs such as shown in Stage III as R-2 to R-5 might develop into one compound reef, just as regressive overlap sands cover wide areas. Wave action would also tend to destroy the dead reefs and thus give rise to continuous

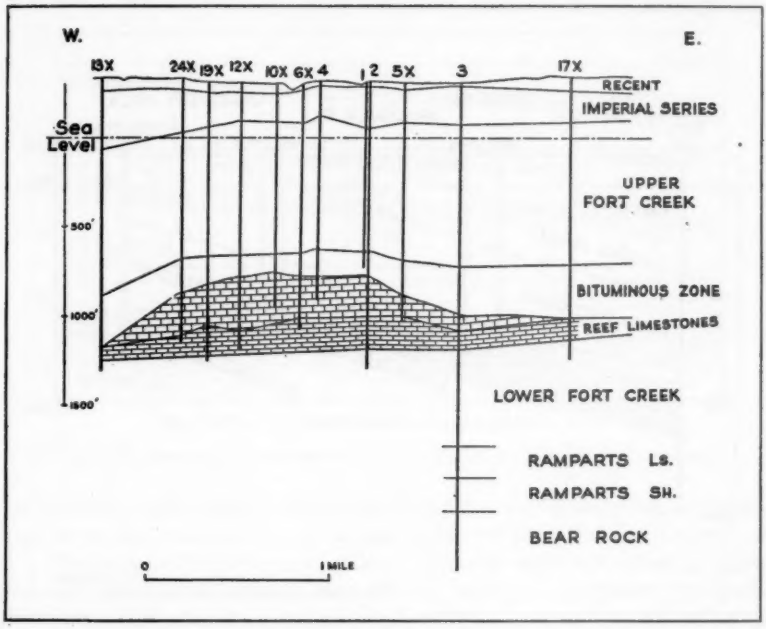


FIGURE 10.—*Transverse cross section of Norman Wells*

sheets of brecciated reef material. This is the present interpretation of the D-2 producing zone at Leduc, which contains anhydrite, red shale, and other material closely related to the back-reef facies. Several ideas of regressive overlap of reefs have already been presented by King (1942) and Lang (1937), but the transgressive type has not, to the writer's knowledge, been described.

VARIATION OF SEA-BOTTOM SLOPE

The development of sizable transgressive and regressive bioherms above hypothesized assumes uniform slope of the sea bottom and concentration of reef growth only when the strand line halted sufficiently long for sizable bioherms to develop. However, many other factors might produce a concentration of reef-forming organisms, such as a variation of the topographic configuration of the bottom of the advancing sea. A sea, containing bioherm-forming organisms and advancing gradually and uniformly over a sea bottom of even slope (all other things being equal) would produce a layer of reef-forming material of uniform thickness—termed the "biostrome" by

Cumings (1932). If, however, the sea floor were not of constant gradient (Fig. 12) the bioherm-forming organisms might be concentrated at changes of slope in spite of a uniformly advancing sea. Figure 13 shows four stages of an advancing sea in

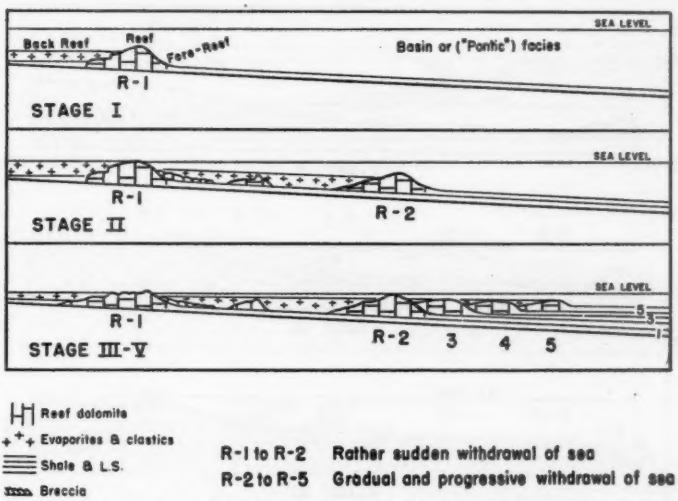


FIGURE 11.—*Reef development during regression of the sea*

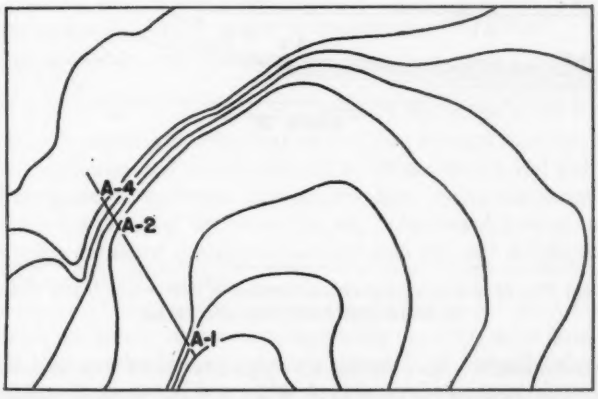


FIGURE 12.—*Idealized map showing configuration of basin over which sea advanced*

A-2 to A-4, steeper slope

which a transgressive development of bioherms is postulated. It is assumed that A-1 could not maintain its growth, and died. From Stage I to Stage II there would be little possibility of large-scale bioherm development between A-1 and A-2 because of the very gentle slope of the sea floor. When the sea level had reached the steeper

slope indicated at A-2, reef-forming organisms should be concentrated along this during the last stages of growth of Bioherm A-1 the strand line rose, and Bioherm steeper slope because the ciliated larvae would require less distance to travel to find

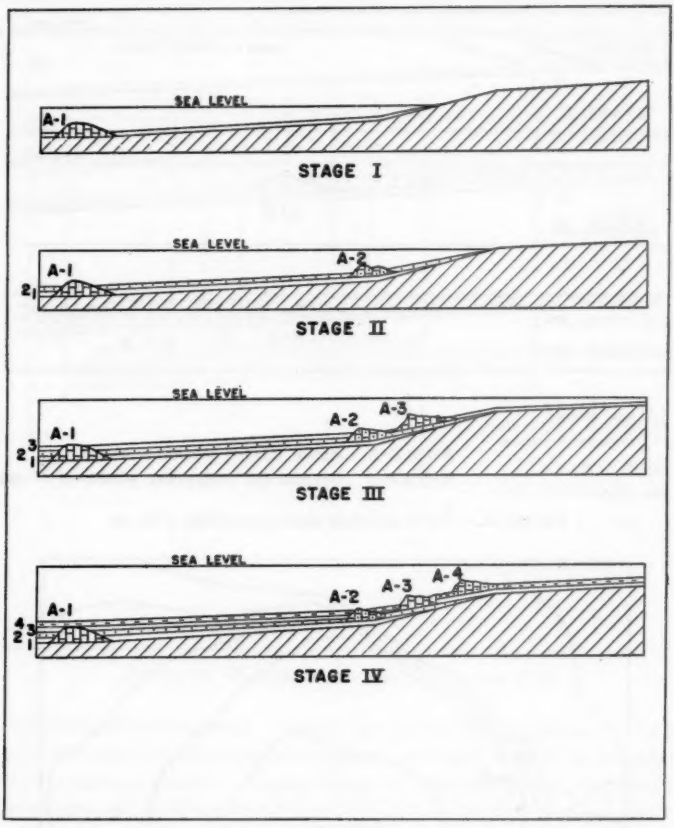


FIGURE 13.—*Ideal diagram showing concentration of transgressive type of bioherm on steeper slope during advance of the sea*

a suitable environment. Also, during an equal interval of time and an equal rise in sea level, more opportunity for growth of the bioherm by stolonation or budding is afforded. The same applies from Stage II to III, and to Stage IV. Thus, all other factors equal, there should be a concentration of bioherm accumulation on the steeper slope, or on a platform.

The same reasoning applies to bioherms developed during regression (Fig. 14). The various stages of regression have not been shown individually, but the final theoretical picture of the three stages is illustrated as having been concentrated along the steeper slope, with the back-reef or shoreward facies to the right. Owing

to lowering of the sea level, wave action would probably have destroyed some of the earlier reefs, thus giving rise to reef breccias as well as leveling off of the tops of the reefs.

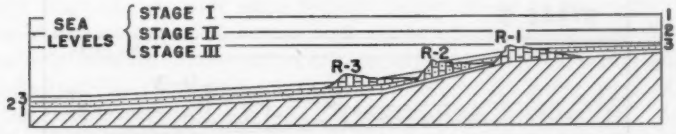


FIGURE 14.—*Ideal section showing development of regressive bioherms concentrated on steeper slope*

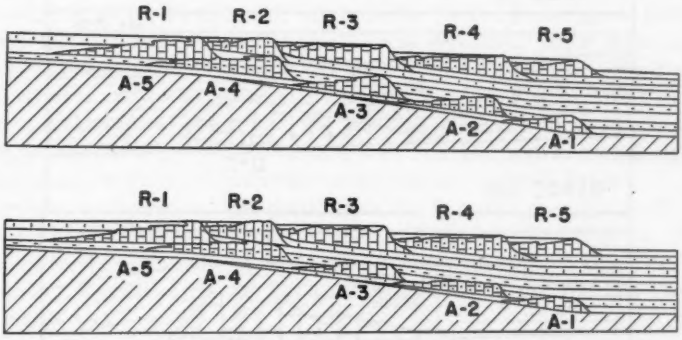


FIGURE 15.—*Ideal section showing bioherms deposited on steeper slope during transgression of sea (A-1 to A-5) and during regression of sea (R-1 to R-5)*

In lower section transgressive bioherms A-1 to A-4 have been truncated, giving rise to local unconformities.

Figure 15 depicts the development of a series of transgressive (A-1 to A-5) bioherms, showing the maximum advance of an invading sea, and then the development of a series of regressive (R-1 to R-5) bioherms. Bioherm A-5 and R-1 is regarded as one and the same; it represents the one developed during maximum advance of the sea and the first stage of the retreating sea. Shoreward from it the back-reef facies were being deposited contemporaneously with the reef development as well as the fore-reef and "pontic" facies.

During advance of the sea the transgressive bioherms A-1 to A-4 might have undergone some submarine destruction, depending upon the wave base and rate of submergence, thus causing the tops of the bioherms to be beveled before deposition of the succeeding clastic sediments. This would give rise to what might be mistaken for large-scale unconformities (Fig. 15B). Such false or apparent unconformities would show a progressive upward shift in the stratigraphic section. Field observations of such a local condition could cause the erroneous conclusion that a major unconformity is under observation. Possibly some of the West Texas and New Mexico Permian correlation disagreements might be due to analogous conditions, and an application of these simple principles could conceivably eliminate some of the present disagreements of correlation.

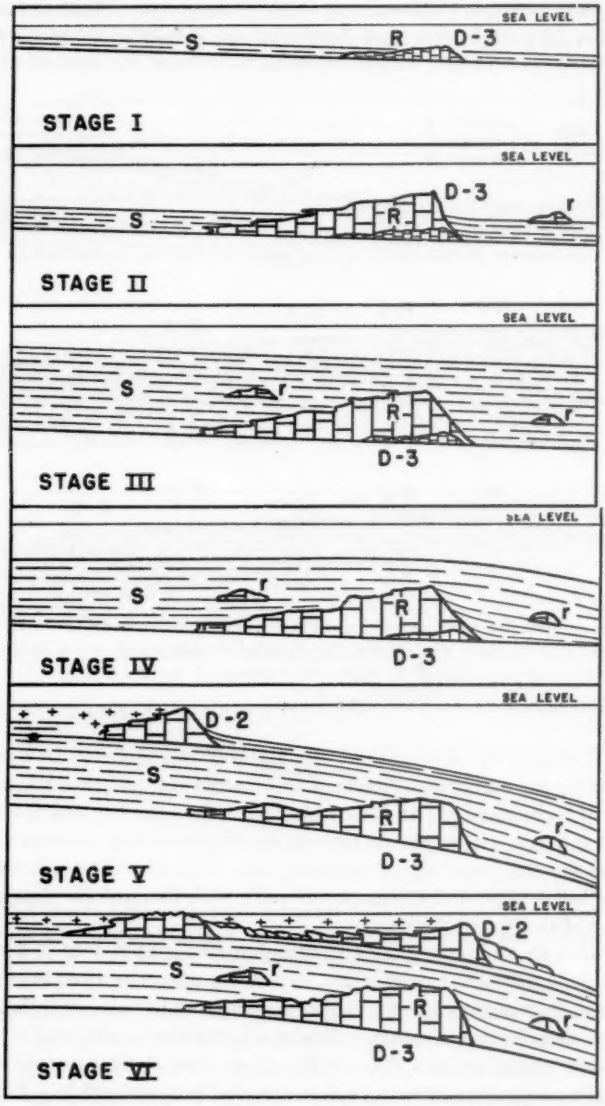


FIGURE 16.—*Hypothetical development of D-3 bioherm*

S—Shale; R—Reef; r—Small reefs; +—Evaporites and clastics; I—Submergence; II—Upward growth of reef; III—**Burial by shale and limestone;** IV—Burial of D-3 reef and draping of shale over it; V and VI—Growth of D-2 reef during temporary withdrawal of sea forming blanket deposit over D-3 reef

SUGGESTED BIOHERM OR REEF HISTORY FOR LEDUC AREA

The following succession of events is postulated: Figure 16, Stage I, indicates a reef in its incipient stages; because of gradual submergence, it grew upward, as shown in Stage II. Another small bioherm began growth at the right. Similar ones could develop anywhere within reach of the ciliated larvae from the parent reef, but only those that anchored in a suitable environment would continue to grow. It is postulated that the large reef is the D-3 bioherm of the Leduc area. At Stage III the sea level has risen sufficiently to cover this D-3 reef with shale.

In Figure 16, Stage IV, the shale deposited over the D-3 reef has settled and shows what might be interpreted as structural dip. In Stage V another reef has developed at the extreme left on the sediments which overlie the D-3 bioherm, and behind this new reef the back-reef phase of evaporites was deposited. With recession other reefs developed seaward, as indicated on Stage V, and the old reefs were brecciated due to solution and/or wave action. This reef is covered by back-reef sediments (*i.e.*, evaporites and red shale), as is the D-2 zone at Leduc. A series of regressive overlapped reefs develops, and oscillation of the strand line, with an overall regression, would produce a uniform or blanketlike reef deposit such as the D-2 zone.

Regression finally reaches the point where the D-2 zone overlaps the D-3 zone, with shale between them, as shown on the Leduc cross section (Fig. 7). Further regression would extend the regressive overlap development of this zone off the illustration. Shoreward (to the left on these drawings), the D-2 and D-3 zones might merge.

APPLICATION TO WEST TEXAS-NEW MEXICO PERMIAN BIOHERMS

Paleogeographic maps of the late Permian of North American indicate that this was an era of overall withdrawal of the Paleozoic epicontinental seas. This applies to North American in general, and to the West Texas-New Mexico region in particular, as attested by examination of Schuchert's well-known paleogeographic maps, and more detailed ones prepared for the West Texas-New Mexico area by King (1942) and Hills (1942). More specific is King's cross section of the Guadalupe Peak area, on which the recession of the sea during deposition of the El Capitan reef limestone is strikingly indicated by the basinward migration of the reefs. According to Hills, Lloyd, King, Skinner, Lang, Adams, and others,[4] the withdrawal of the sea was accompanied by minor rhythmic advances and retreats, with an overall withdrawal. This is expectable during a period such as the Permian, which preceded major diastrophic movements that terminated the Paleozoic. Nevertheless, Darwin's contention that bioherms or reefs grow only during submergence or a rise of the strand line seems to create a paradox when applied to the reefs in the West Texas-New Mexico area. If one accepts Darwin's views, the tremendous growth of reefs during El Capitan time must be explained by postulating a pronounced pulsating recession of the sea. However, this is not the only possible explanation, since a basinward growth of the El Capitan reefs is obvious and is so well illustrated in

[4] Specific references to all the contributions in the pages of the Bulletin of the American Association of Petroleum Geologists on this subject are not regarded as practical or necessary, but the reader is urged to study all of these.

King's section at Guadalupe Peak. Evidently reefs or bioherms can develop during an overall, gradual lowering of the strand line on a large scale, without extreme oscillations.

SUMMARY

The main characteristics of the regressive type of reef or bioherm deposition such as the El Capitan type are four distinct facies of deposition: (1) back-reef evaporites, clastics, and brecciation; (2) massive, porous reef or bioherm accumulation; (3) fore-reef, well-bedded clastics such as shale, limestone, sandy limestones, and dolomite, with occasional wave-developed or slumped breccia; and (4) basin or "pontic" well-bedded gray to black shale, sandy shale, and limestone.

Facies (1) and (2) overlap (3) and (4) during normal retreat of the sea. The regressive type of bioherm or reef may contain back-reef types of sediments such as red shale and anhydrite, but the transgressive type lacks the typical back-reef facies (Lloyd, 1929), so that the shoreward and basinward deposition, and the later overlying sediments are essentially the same. In many instances well-bedded "pontic" shales surround the bioherms, as at Norman Wells; in others, such as the smaller bioherms in Southwest Ontario, the surrounding sediments are limestones.

Both the transgressive and regressive types could produce blanket or compound reefs extending laterally for many miles, depending on whether or not the transgression or regression was pulsating.

Therefore, with extreme pulsation during both transgression and regression, a hybrid type of reef and facies might develop, which could be deciphered only after considerable data were made available.

Destruction of the upper part of a transgressive bioherm by wave action and subaerial erosion is less likely than in the case of the regressive type, but wave-base and submarine erosion is probable.

Owing to the environment and conditions under which a transgressive-type reef develops, the absence of evaporites and other related backreef types of sediments within the bioherm and surrounding it is, *ipso facto*, a prerequisite. The Norman Wells reef in particular and the Leduc D-3 to a lesser degree are both intimately associated with the "pontic" or basin-type sedimentary facies, thus suggesting a different history of growth as compared to either the late Permian or to the Devonian D-2 type of bioherm. This does not preclude the possibility, and indeed the probability, that transgressive types of reefs formed in the Permian, and might be discovered by deep drilling in the basin areas.

REFERENCES CITED

Adams, J. E. (1930) *Origin of oil and its reservoir in Yates Pool, Pecos County, Texas*, Am. Assoc. Petrol. Geol., Bull., vol. 14, p. 705–717.

——— (1934) *Origin, migration, and accumulation of petroleum in limestone reservoirs in the western United States and Canada*, in *Problems of petroleum geology*, Am. Assoc. Petrol. Geol. (Sidney Powers Mem. Vol.), p. 347–363.

Alberta Society of Petroleum Geologists (1941) *Possible future oil provinces in western Canada*, Am. Assoc. Petrol. Geol., Bull., vol. 25, p. 1447–1456.

Cumings, E. R. (1932) *Reefs or bioherms*, Geol. Soc. Am., Bull., vol. 43, p. 331–352.

Darwin, Charles (1897) *Structure and distribution of coral reefs*, D. Appleton & Co., New York, 34th ed., 344 pages.

Hills, J. M. (1942) *Rhythm of Permian seas*, Am. Assoc. Petrol. Geol., Bull., vol. 26, p. 217–255.

Howard, W. V. (1934) *Accumulation of oil* and *gas in limestone*, in *Problems of petroleum geology*, Am. Assoc. Petrol. Geol. (Sidney Powers Mem. Vol.), p. 365–375.

King, P. B. (1942) *Permian of west Texas and southeastern New Mexico*, Pt. II of West Texas-New Mexico symposium, Am. Assoc. Petrol. Geol., Bull., vol. 26, p. 535–763.

Lang, W. B. (1937) *Permian formations of the Pecos Valley of New Mexico and Texas*, Am. Assoc. Petrol. Geol., Bull., vol. 21, p. 833–898.

Link, W. K. (1947) *Oil, its origin and accumulation* (Discussion quoted by F. M. Van Tuyl and B. H. Parker), World Oil, vol. 126, no. 7, pt. 1, p. 39–41.

Lloyd, E. Russell (1929) *Capitan limestone and associated formations*, Am. Assoc. Petrol. Geol., Bull., vol. 13, p. 645–658.

Rutherford, R. L. (1939) *Edmonton area*, Geol. Survey Canada, Dept. Mines Res.

Skinner, John W. (1946) *Correlation of Permian of West Texas and southeast New Mexico*, Am. Assoc. Petrol. Geol., Bull., vol. 30, p. 1857–1874.

Vaughan, T. W. (1940) *Ecology of modern marine organisms with reference to paleogeography*, Geol. Soc. Am., Bull., vol. 51, p. 433–468.

7 Grenadier Heights, Toronto 3, Canada.

Manuscript Received by the Secretary of the Society, April 26, 1948.

PLATE 2.—PHOTOGRAPHS OF CORES

Figure

1.—BRECCIATED DOLOMITE AND DOLOMITIC LIMESTONE FROM UPPER 100 FEET OF D-1 ZONE
Solution breccia developed at time of unconformity. Dark angular fragments are dolomite saturated with heavy oil. Diameter of core 3 inches. (Photo by D. B. Layer)

2.—BRECCIATED DOLOMITIC LIMESTONE FROM UPPERMOST PART OF D-1 ZONE
Dark fragments are oil-saturated limestone and dolomite. Diameter of core 3 inches. (Photo by D. B. Layer)

3.—BRECCIATED OIL-STAINED DOLOMITE AND LIMESTONE FRAGMENTS INTERBEDDED IN CALCAREOUS MATRIX
From upper part of D-1 zone. Diameter of core 3 inches. (Photo by D. B. Layer)

4.—VERY POROUS SPECIMEN FROM D-2 ZONE, WHICH LACKS PERMEABILITY BECAUSE PORES ARE INTERIOR OF CORALLITES WHICH ARE NOT CONNECTED WITH ONE ANOTHER
Anhydrite occurs in some of the "vugs", and many cores show complete infilling of the primary pores by dolomite and anhydrite. Diameter of core 3 inches. (Photo by D. B. Layer)

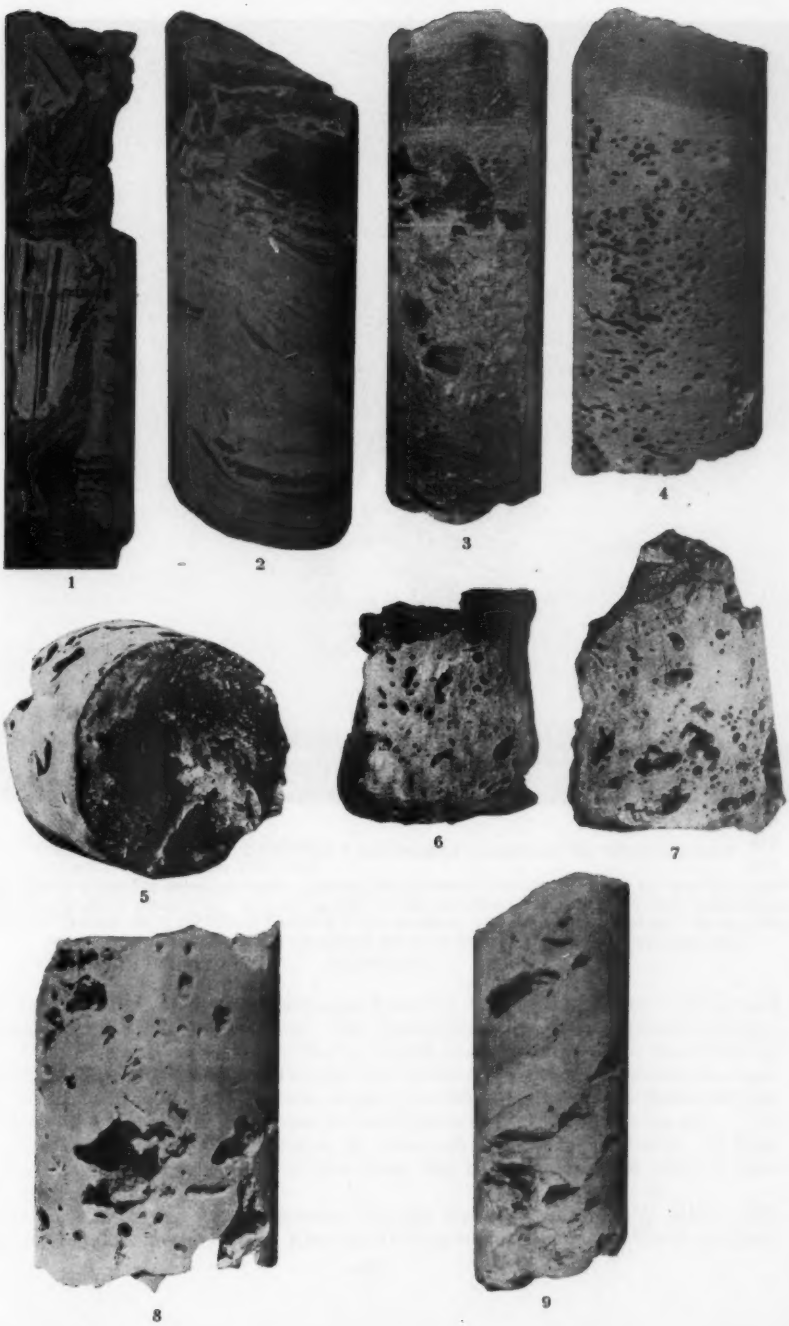
5.—TOP VIEW OF CORE FROM GAS-CAP PORTION OF D-3 ZONE
Dark material is a solidified bitumen (pyrobitumen) characteristic of the gas cap. Primary porosity is lined with thin layer of dolomite crystals and the pyrobitumen. Diameter of core 3¾ inch.

6.—TYPICAL CORE FROM D-3 ZONE IN OIL-SATURATED PORTION
Showing primary porosity developed at time of deposition. Core is essentially all granular dolomite. Diameter of core 3¾ inches.

7.—CORE FROM D-3 ZONE OIL HORIZON WHICH BROKE ALONG FRACTURE PLANE
Showing excellent primary porosity. Diameter of pieces 3¾ inches.

8.—CORE FROM D-3 OIL ZONE
Showing excellent primary porosity. Diameter of core 3¾ inches.

9.—CORE FROM WATER LEVEL IN D-3 ZONE
Showing orientation of primary pores parallel to apparent bedding, which is probably depositional near the face of the reef, or due to slumping during growth of reef. Diameter of core 3 inches. (Photo by D. B. Layer)



PHOTOGRAPHS OF CORES

PHOTOGRAPH OF IMPERIAL LEDUC No. 3 BLOWING INTO PRODUCTION

When an oil well first "blows in" the oil and natural gas coming up from the producing formation below are contaminated with mud, water and chemicals used in drilling the hole. Since these would clog up the separators and the storage tanks, the flow is turned into a flare and burned for a few minutes until the well cleans itself out. This is a common oil-well procedure. (Imperial Oil Ltd. photograph).

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 60, PP. 403-438 4 PLS. MARCH 1949

DEVONIAN-MISSISSIPPIAN FORMATIONS OF SOUTHEAST IOWA

BY LEO A. THOMAS

CONTENTS

	Page
Abstract	403
Introduction and acknowledgments	404
Historical summary	404
Maple Mill shale	407
Definition	407
Stratigraphy	407
Conodont assemblage	407
Correlation	408
Conodont genera and species from the Maple Mill	408
English River and Prospect Hill siltstones	408
General statement	408
Conodont assemblages	409
Correlation	410
Louisiana limestone	410
Definition	410
Correlation of the Louisiana with the Burlington section	413
Conclusions	413
Sections and collection localities	414
Description of species	416
References cited	430
Explanation of plates	433

ILLUSTRATIONS

Plate	Facing page
1. Conodonts from the Maple Mill shale	434
2. Conodonts from the Maple Mill shale	435
3. English River and Prospect Hill conodonts	436
4. English River and Prospect Hill conodonts	437

ABSTRACT

A study of the conodont assemblages from the Maple Mill, Grassy Creek, and Louisiana formations discloses that these assemblages are closely related and also that these assemblages are more closely related to conodonts from unquestionably Devonian rocks than to an assemblage from rocks of undoubted Mississippian age. I have assigned the Maple Mill shale to the upper Devonian because of these reasons; therefore, the Maple Mill shale must be redefined to indicate its Devonian age. The Maple Mill and Grassy Creek shales, of Iowa and Missouri respectively, are time equivalents, because subsurface studies show that the 2 shales grade laterally into each other.

The methods employed to determine the age and correlation of the Maple Mill shale were applied to the English River and Prospect Hill siltstones. These methods

indicate that these siltstones are lower Mississippian, and that they are time equivalents of the Bushberg and Hannibal formations of Missouri.

The Louisiana limestone of Missouri has been correlated with the McCraney limestone of Iowa because of similarity of a few macro-fossils and lithologic characteristics. Conodont studies suggest that the Louisiana is related to the Grassy Creek, whereas the McCraney is related to the Hannibal. This difference precludes the possibility of the two limestones being correlated as time equivalents.

INTRODUCTION AND ACKNOWLEDGMENTS

This report sets forth the results of a study of the Devonian-Mississippian boundary, and Lower Mississippian beds of southeastern Iowa. Conodont assemblages from this division of the geologic column in Iowa have not been described previously.

Conodonts are believed to be a good stratigraphic tool, and they are presented here as evidence to establish the Devonian-Mississippian boundary, and to determine the ages of the Lower Mississippian units in Iowa so that these units may be more accurately correlated with their equivalents in Missouri.

All formations between the Burlington and Cedar Valley limestones, except the Sweetland Creek shale, were examined in southeastern Iowa. Three of these units, the Maple Mill shale, the English River, and Prospect Hill siltstones, contained conodont assemblages.

The rock units studied form an almost continuous northwest-southeast belt of exposures across the southeastern corner of Iowa. The exposures are confined to the bluffs of the Mississippi, Iowa, and English rivers and their tributary streams. A complete section is exposed at the city of Burlington and in the creek valleys immediately north. The rocks dip beneath the flood plain of the Mississippi River in northern Des Moines County, but they reappear in the banks of Smith Creek in Louisa County. Several good exposures occur in the creeks that enter Iowa River in the lower basin of Long Creek south of Columbus Junction. Northwestward from there the series is covered, but it crops out along the bluffs of the English River in Washington County, where some of the type sections are located.

The field work was started during the summer of 1946, continued intermittently during the fall and winter of 1946–1947, and completed in the summer of 1947.

Figured specimens of conodonts described in this report have been placed in the University of Missouri conodont collections.

E. B. Branson directed the work and generously gave his time in the field. His counsel concerning stratigraphy and the numerous other problems that arose was always available.

M. G. Mehl photographed the specimens and aided in the preparation of the plates. His advice on the systematic description of the conodonts was very helpful.

The staffs of the Iowa and Missouri Geological Surveys allowed me to examine well samples and made available other data involved.

HISTORICAL SUMMARY

Meek and Worthen (1861) applied the name "Kinderhook Group" to the beds lying between the "black slate and the base of the Burlington limestone" at Kinderhook, Pike County, Illinois.

Branson (1938, p. 5) believed the term "Lower Mississippian" should replace "Kinderhook", "as several Devonian formations have been included in the Kinderhook the name is not suitable for a Mississippian division."

I shall use the term "Lower Mississippian" rather than "Kinderhook" because evidence presented in this paper substantiates Branson's conclusion.

The following modified section (Weller, 1899) is used as a standard for comparison of Lower Mississippian and Upper Devonian rocks in southeastern Iowa.

		Feet
7. (Wassonville?)	Limestone, soft, buff, gritty	3–5
6. (North Hill)	Limestone, white, oölitic	2–4
5. (Prospect Hill)	Sandstone, fine grained, yellow	6–7
4. (McCraney)	Limestone, fine grained, compact	12–18
3.	Limestone, impure, filled with *Chonetes;* sometimes associated with a thin oölite band	½
2. (English River)	Sandstone, argillaceous, friable, soft, bluish, filled with fossils in the upper part, the most abundant of which is *Chonopectus fischeri*	25
1. (Maple Mill)	Shale, soft, blue, argillaceous (exposed)	60

The parenthetical insertions are added for clarity in all sections.

Keyes (1892; 1895) correlated the Wassonville limestone with the Chouteau formation of Missouri. The relation of the North Hill oölitic limestone with the Lower Mississippian units of Missouri was doubtful. He considered the English River, McCraney, and Prospect Hill divisions as representing the Hannibal formation of Missouri. The Maple Mill shale was correlated with the Grassy Creek shale of Missouri.

Bain (1895a) described a section of Lower Mississippian rocks (the Maple Mill section) in Washington County, here modified as follows:

SE¼ NW¼ sec. 8, T. 77 N., R. 8 W.

		Feet
4. (Wassonville)	Limestone, ferruginous, arenaceous in places, fine-grained, red, containing numerous casts of fossils and with thin chert layers 2–8 inches thick, also fossiliferous	10
3. (English River)	Sandstone, or gritstone, very fine grained, white to buff, very fossiliferous	18
2. (Maple Mill)	Limestone, fine grained, non-fossiliferous	1½
1.	Shale, argillaceous, dark blue to drab, becoming almost black in places	12

The type locality of the Wassonville limestone is 1½ miles upstream from this section. Bed 3 was named the English River sandstone, and beds 1 and 2 were named the Maple Mill shale.

Bain (p. 139) classified the Sweetland Creek shale as Devonian, but he indicated that there was uncertainty as to both the position of the Devonian-Mississippian boundary, and the assignment of the Maple Mill shale to the Mississippian period. He states:

"There is at the top of the Devonian a series of shales containing Devonian forms, and on the other hand at the base of the Carboniferous an exactly similar shale interbedded at the top with gritstones containing Carboniferous forms.* * * Some of the evidence at hand supports the belief that the shale at the top of the Devonian and that at the base of the Carboniferous is the same. It is not improbable that ultimately a considerable portion of the beds now recognized as Kinderhook may be proved to be pre-Carboniferous."

Weller (1899) thought that the Maple Mill, the English River, and the thin oölite band at the base of the McCraney were pre-Louisiana, because the earliest indication of the Louisiana limestone fauna occurred in the McCraney, which he believed to be the northern extension of the Louisiana formation.

Weller (1909, p. 273) concluded that the English River and Maple Mill units at Burlington contained both Devonian and Mississippian fossils and were transitional from Devonian to Mississippian, but that they should be classified as Lower Mississippian. He states that,

"the lower 100 feet of unit 1 (Maple Mill) lies beneath the level of the Mississippi River, so that contact with the underlying formation and the age of the subjacent bed is not known. The lower bed, however, is probably Devonian, and is not unlikely the Cedar Valley limestone, since that formation lies unconformably beneath the Kinderhook beds farther south. If this is the case these lower shales of the Kinderhook correspond in position with the Sweetland Creek shales of the Upper Devonian in Muscatine County, Iowa. There is, however, insufficient faunal evidence upon which to base a definite correlation of these two shales."

Van Tuyl (1921) revised the Lower Mississippian section at Maple Mill, here modified as follows:

		Feet
6. (Wassonville)	Limestone, yellowish, dolomitic; massive; with occasional bands of darker chert	16
5. (North Hill)	Limestone, brownish, dolomitic; indications of obscure oölitic texture	2
4. (Prospect Hill)	Siltsone, ash colored, shaly in middle part; grading gradually upward into the bed above	1
3. (McCraney)	Limestone, brown to red; dense, but weathers to soft thin layers	1
2. (English River)	Siltstone, ash colored, soft, with molds of fossils	13
1. (Maple Mill)	Concealed to level of river	

Beds 1 and 2 of Bain's original section are concealed, and Bain's English River is divided into three members (beds 2, 3, and 4).

Van Tuyl believed that the English River siltstone at Burlington represented "only the lower thirteen feet of Bain's original section and for that reason should be revised." This interpretation makes the thin dolomitic limestone member (bed 3) and the top siltstone (bed 4) the attenuated representatives of the McCraney and Prospect Hill of the Burlington section. Van Tuyl realized that the faunas of the two areas were slightly different so that this correlation could not be made definite.

Moore (1928) applied the term "Prospect Hill" member of the Hannibal formation to the upper silt of the Burlington section. It was believed to underlie the Chouteau formation and to constitute the top member of the Hannibal formation. Moore proposed the term "McCraney" at the same time for the lithographic limestone beneath the Prospect Hill siltstone. The name, as proposed by Moore, was incorrectly spelled McKerney but was corrected by Weller and Sutton (1940).

Weller and Sutton (1940, p. 785) considered the Sweetland Creek shale equivalent to the Maple Mill shale. They also say,

"the McCraney limestone is lithologically similar to the Louisiana, and as these two formations have not been observed in the same section it is possible that they are equivalent. If so the Maple Mill shale and the English River siltstone are members of the Saverton. Both of these names, however, are derived from localities in Iowa considerably removed from the various well known localities of

Kinderhook sections and their relations to each other and to these sections have not yet been fully established."

Cooper *et al.* (1942) classify the Grassy Creek, Louisiana, and their equivalents as either Mississippian or Devonian.

Easton (1944) questionably referred the Maple Mill shale to the Lower Mississippian.

Weller *et al.* (1948) classify the Maple Mill, Grassy Creek, and other formations that occupy a similar position as Lower Mississippian or Upper Devonian.

MAPLE MILL SHALE

DEFINITION

The age of this poorly fossiliferous shale that occupies the interval between definitely recognized Mississippian divisions has been a disputed question.

The Maple Mill shale was originally defined as including, "everything below the English River sandstone and above the Devonian formations." It is here redefined as the uppermost Devonian shale.

STRATIGRAPHY

The Maple Mill conformably underlies the English River siltstone. In Washington County it changes abruptly from a blue shale, containing carbonaceous material, to the fine blue quartz silts of the English River. The English River unit has been considered to be the top fossiliferous and siliceous zone of the Maple Mill shale.

The Maple Mill and Sweetland Creek shales do not occur together on the surface, and their relationship is not clear.

CONODONT ASSEMBLAGE

I have recorded 46 species of conodonts representing 19 genera from the Maple Mill shale. Conodont genera considered Devonian by Branson and Mehl are abundant. The Maple Mill assemblage belongs in a closely related group of assemblages that occur in the Grassy Creek, Sweetland Creek, Gunendewa, middle New Albany, and Ohio shales, and others.

The "diagnostic" Devonian genera from the Maple Mill shale are not present in the English River siltstone, and the boundary between the assemblages from these two units is sharp.

The conodont assemblage from, and near, the type, locality of the Maple Mill shale varied so considerably from the assemblage in the same shale near Burlington as not to be recognized as the same. Devonian genera were not common at Burlington, but there was an abundance of *Polygnathus triangularis* Branson and Mehl. Near the type locality *Polygnathus semicostata* Branson and Mehl is abundant, and there is a preponderance of such genera as *Palmatolepis*, *Polylophodonta*, *Ancyrognathus*, and *Nothognathella*. *Spathognathodus inornatus* (Branson and Mehl) and fragments of *Hindeodella* are common in all samples. Other genera present, in varying number, in the Maple Mill shale include *Icriodus*, *Prioniodus*, *Euprioniodina*, *Ligonodina*, and *Lonchodina*.

Many samples contained representatives of the family Distocodidae, recognized as

pre-Devonian and considered to be contamination. These forms are not figured in this work because to do so might be misleading.

CORRELATION

A comparison of the conodont assemblage from the Maple Mill shale shows that 30 per cent of its species are present also in the Grassy Creek shale of Missouri. This percentage is too low for exact correlation, but the two assemblages are similar.

University of Missouri conodont collections from the Sweetland Creek shale substantiate Miller and Youngquist's (1947) late Devonian age for that shale. The conodont assemblages of the Maple Mill and Sweetland Creek shales are different in many ways, which may tend to disprove a direct correlation between the two. The differences may be, however, no more than a response to different environmental conditions.

Examinations of well cuttings in the Iowa and Missouri Geological Survey collections indicate that the Maple Mill shale of Iowa grades laterally into the Grassy Creek shale of Missouri.

The similarity of conodont assemblages, and the lateral gradation between the Maple Mill and Grassy Creek shales clearly shows that these two shale units are time equivalents.

CONODONT GENERA AND SPECIES FROM THE MAPLE HILL SHALE

ANCYROGNATHUS irregularis Branson and Mehl
A. minuta Thomas, n. sp.
BRYANTODUS lateralus Thomas, n. sp.
B. millensi Thomas, n. sp.
B. sp? 3
DIPLODODELLA alternata (Branson and Mehl)
D. sp. A.
EUPRIONIODINA iowaenisis Thomas, n. sp.
E. lateralis Thomas, n. sp.
HIBRARDELLA longipostica Thomas, n. sp.
H. plana Thomas, n. sp.
H. recurvata Thomas, n. sp.
HINDEODELLA cf. *H. corpulenta* Branson and Mehl
H. cf. *H. gladiola* E. R. Branson
H. sp?
H? sp.
ICRIODUS constrictus Thomas, n. sp.
I. cf. *I. rectus* Youngquist and Peterson
LIGONODINA delicata Branson and Mehl
L. robusta Branson and Mehl
L. sp. A.
LONCHODINA cf. *L. prava* Huddle
L. sp. A.
L. sp. B.
NOTHOGNATHELLA gigantea Thomas, n. sp.
N. minuta Thomas, n. sp.
OZARKODINA cf. *O. regularis* Branson and Mehl
O. mellensis Thomas, n. sp.
PALMATOLEPIS distorta Branson and Mehl
P. glabra Ulrich and Bassler
P.? irregularis Thomas, n. sp.
P. perlobata Ulrich and Bassler
POLYLOPHODONTA acuta? Thomas, n. sp.
POLYGNATHUS perplana E. R. Branson
P. granulosa Branson and Mehl
P.? millensis Thomas, n. sp.
POLYGNATHUS perplexa ? Thomas, n. sp.
P. sanduskiensis Stauffer
P. semicostata Branson and Mehl
P. trangularis Branson and Mehl
P. sp. A.
PELEKYSGNATHUS communis Thomas, n. sp.
P. costata Thomas, n. sp.
P. inclinata Thomas, n. sp.
P. nodosa Thomas, n. sp.
PRIONIODELLA ? sp.
PRIONIODUS molestus Branson and Mehl
P. obtusus Branson and Mehl
SPATHOGNATHODUS crassidentatus (Branson and Mehl)
S. flexus Thomas, n. sp.
S. inornatus (Branson and Mehl)
S. strigosus (Branson and Mehl)
TRICHONODELLA robusta (Branson and Mehl)

ENGLISH RIVER AND PROSPECT HILL SILTSTONES

GENERAL STATEMENT

The English River siltstone, named from exposures along the English River in Washington County, is the most persistent and readily recognized of all the Lower Mississippian units of southeastern Iowa, and it lies with apparent conformity on the Maple Mill shale. The English River siltstone is overlain by the McCraney lime-

stone at Burlington, and their boundary is indicated by a leached yellow portion at the top of the English River. The Wassonville limestone lies on the English River siltstone in western Louisa County, but is in contact with the Maple Mill shale in a road cut 1 mile southeast of Kalona. This relation indicates an erosional unconformity at the top of the English River siltstone.

The Prospect Hill siltstone has a small distribution in southeastern Iowa, and is exposed best in the immediate vicinity of Burlington. Exposures are not abundant in Louisa County, but it may be identified as far west as Morning Sun in the valley bluffs of some of the creeks that are tributaries to the Iowa River. This unit was identified in Washington County in the Maple Mill section, and in the east bank of the English River, SW$\frac{1}{4}$, sec. 4, T. 77 N., R. 8 W.

CONODONT ASSEMBLAGES

The conodont assemblages from the English River and Prospect Hill siltstones* (Table 1) indicate a Lower Mississippian age for these rock units. I have identified 40 species representing 17 genera of conodonts from the English River unit, and 32 species representing 15 genera from the Prospect Hill unit. The following genera and species of conodonts, here arranged in descending order of number of individuals, are the important conodonts in these siltstones.

Siphonodella quadruplicata (Branson and Mehl) occurred in nearly every sample. Specimens show considerable variation of size, shape, and ornamentation. This species is very abundant in the English River silt, but it is represented by only a few specimens in the Prospect Hill siltstone.

Siphonodella duplicata (Branson and Mehl) is represented by a few specimens in the English River. This species is so abundant in the Prospect Hill that a large number of them in a sample might be taken as an indicator of this unit.

Siphonodella sexplicata (Branson and Mehl) is sparingly represented in both rock units.

Almost as abundant as the Siphonodellas are many species of the genus *Polygnathus*. Species of this genus show variations among individuals that are so numerous as to make their boundaries uncertain. Some of the smaller specimens of this genus are not described because they are indistinguishable, and their relationships to the larger specimens are uncertain. The most abundant representative of this genus is *P. inornata* E. R. Branson. *P. longipostica* Branson and Mehl is represented by a few specimens.

Solenodella tenera (E. R. Branson) is fairly abundant in these rock units.

Spathognathodus costatus (E. R. Branson) is the dominant species of this genus in these two Lower Mississippian siltstones.

A few specimens of the genus *Pinacognathus* are present in the Prospect Hill siltstone. Why this genus should be present in the Prospect Hill and not in the English River siltstone is somewhat puzzling, but additional collecting from the English River may show its presence.

Ligonodina, *Solenodella*, *Spathognathodus*, and *Pseudopolygnathus* are about equally represented.

*The present paper was in galley proof when the paper by Youngquist and Patterson appeared (Journal of Paleontology, Feb., 1949).

CORRELATION

The English River siltstone has been correlated with all or part of the Hannibal formation of Missouri by Keyes (1892a; 1895), Weller (1900), Van Tuyl (1921), Moore (1928), Weller and Sutton (1940), and Weller *et al.* (1948). A specific comparison shows that 54 per cent of the English River conodont species are also present in the Bushberg and Hannibal formations of Missouri.

Moore (1928) thought the Prospect Hill should be correlated with the Hannibal formation. He indicated that the unit contained a large Chouteau element in its fauna, but he thought that lithologically and faunally it was more closely allied to the Hannibal formation.

A comparison of conodont assemblages shows that 59 per cent of the Prospect Hill are also present in the Bushberg and Hannibal formations, and that 44 per cent of the Prospect Hill species are also present in the English River siltstone.

These Lower Mississippian units are dated by species of the genus *Siphonodella* and *Pinacognathus*. *Siphonodella quadruplicata* (Branson and Mehl) has not been reported from formations that are unquestionably younger than the Hannibal formation. *Siphonodella duplicata* (Branson and Mehl) has been reported from the Chouteau limestone of Missouri by Branson and Mehl (1938), and from the Welden limestone of Oklahoma by Taylor (1942). With such a vertical range the species offers little for precise correlation purposes. *Siphonodella sexplicata* (Branson and Mehl), reported only from the Bushberg sandstone and similar formations, is a more precise age indicator than the other species of this genus.

The genus *Pinacognathus* is not abundantly represented in any Lower Mississippian formation, but it has not been reported from any formation whose age is unquestionably younger than Bushberg. The genus is restricted apparently to basal Lower Mississippian. These restricted genera and species indicate a Hannibal rather than a Chouteau correlation.

Lateral tracing by means of well cores and the similarity of conodont assemblages indicate that the Hannibal formation grades laterally into the English River and the Prospect Hill siltstones of Iowa. The term Hannibal has priority over English River; therefore, the English River and Prospect Hill are considered as members of the Hannibal formation.

LOUISIANA LIMESTONE

DEFINITION

This limestone overlies the Grassy Creek shale and underlies the Hannibal formation in Missouri. The Louisiana has been referred to the uppermost Devonian, and to the lower-most Mississippian by about an equal number of geologists. In this paper, the Maple Mill shale is shown to be a time equivalent of the Grassy Creek shale; the English River, McCraney, and Prospect Hill units are shown to be time equivalents of the Hannibal formation of Missouri. The Louisiana has been considered to be an equivalent of the McCraney limestone of Iowa; therefore, the age of the Louisiana has a direct bearing on the correlation of the Lower Mississippian and Upper Devonian units of Iowa with similar units in Missouri, and the importance of the correct age determination is evident.

TABLE 1.—*English River and Prospect Hill conodonts*

Genera and Species	English River	Prospect Hill
BRYANTODUS planus? Branson and Mehl		x
B. flexus? Branson and Mehl	x	
B. giganteus E. R. Branson		x
B. planus? Branson and Mehl	x	
B. scolops Cooper	x	
B. sp? B.	x	
CENTROGNATHODUS dubius Thomas, n. sp.		x
DIPLODODELLA symmetrica? (Huddle)	x	
D.? sp.	x	
EUPRIONIODINA aphanes Cooper		x
E. symmetrica Thomas, n. sp.	x	
E. sp. A.	x	
GNATHODUS sp. indet.	x	
HIBBARDELLA macrodentata Thomas, n. sp.	x	
H. sp. A.		x
HINDEODELLA curvata Branson and Mehl	x	
H. acuta Branson and Mehl		x
H. sp. indet.		x
H. sp. A.		x
LIGONODINA delicata Branson and Mehl	x	
L. dubia Thomas, n. sp.		x
L. flexuosa Branson and Mehl		x
L. gigantea Thomas, n. sp.		x
L. minaut Thomas, n. sp.	x	
LONCHODINA sp. C.		x
OZARKODINA cf. *O. elongata* Branson and Mehl	x	
O. sp. A.		x
PALMATODELLA sp. indet.	x	
PINACOGNATHUS cf. *P. profundus* (Branson and Mehl)		x
POLYGNATHUS anida Cooper	x	
P. perplana E. R. Branson	x	
P. communis Branson and Mehl	x	x
P. concava Thomas, n. sp.	x	
P. corrugata E. R. Branson		x
P. gigantea Thomas, n. sp.		x
P. inornata E. R. Branson	x	x
POLYGNATHUS lobata Branson and Mehl	x	
P. longipostica Branson and Mehl	x	x
P. nodosa Thomas, n. sp.	x	
P. orthoconstricta Thomas, n. sp.		x
P. permarginata E. R. Branson	x	x
P. scapha Cooper	x	
P. triangularis Branson and Mehl	x	
P. sp. B.	x	x
P. sp. C.	x	
PRIONIODUS aphanes (Cooper)	x	x
P. barbatus Braonson and Mehl	x	x
P. corniger E. R. Branson	x	x
P. alatus? Hinde		x

TABLE 1.—*Concluded*

Genera and Species	English River	Prospect Hill
PSEUDOPOLYGNATHUS cf. *P. asymmetrica* E. R. Branson		x
P. brevimarginata E. R. Branson	x	x
P. constrictiterminata Thomas, n. sp.	x	
P. cf. *P. crenulata* E. R. Branson		x
P. prima Branson and Mehl		x
SIPHONODELLA duplicata (Branson and Mehl)	x	x
S. quadruplicata (Branson and Mehl)	x	x
S. sexplicata (Branson and Mehl)	x	x
SOLENODELLA tenera (E. R. Branson)	x	x
S. cf. *S. bialata* (Branson and Mehl)	x	
S. lateranodosa Thomas, n. sp.	x	
SPATHOGNATHODUS aciedentatus (E. R. Branson)	x	
S. costatus (E. R. Branson)	x	x
S. crassidentatus (Branson and Mehl)	x	x
S. delicatulus (E. R. Branson)	x	
S. inornatus (Branson and Mehl)	x	
S. irregularis (E. R. Branson)	x	
S. quintidentatus Thomas, n. sp.		x
S. strigosus (Branson and Mehl)		x
S. tridentatus (E. R. Branson)	x	
S. sp. A.	x	
S. sp. B.	x	
SUBBRYANTODUS minutus Thomas, n. sp.	x	
TRICHONODELLA sp?	x	

Williams (1943) described the invertebrate fauna of the Louisiana formation and wrote that

"many of the Louisana species occur also in the blue mudstone of the underlying Saverton (Grassy Creek)* * * and for this reason the lower limit of the formation is not a distinct paleontological line.* * * Some or all of the blue mudstone (Grassy Creek) should be included in the formation if the lower boundary is selected on a paleontological basis rather than on a lithological basis, but it seems best to rely upon lithology and place the lower limit of the formation above the blue mudstone."

His faunal chart showed that 38 per cent of the species that occur in the upper part of the Grassy Creek also occur in the dense limestone and its clay partings, and that 50 per cent of the Grassy Creek species are present in the yellow-brown mudstone beneath the limestone. The macro-faunal evidence, presented by Williams indicates a similar age for the Grassy Creek and Louisiana formations.

The "Saverton" as used by Williams, is included in the "Grassy Creek" by Branson and Mehl (1933).

Studies convinced Branson and Mehl (1933) that the

"Grassy Creek passes into the Louisiana limestone without break, and that the shale macro-fauna is the same as that of the Louisiana,* * * and wherever the Grassy Creek shale belongs, the Louisiana limestone goes with it."

Branson (1944) published a list of conodonts from the Louisiana limestone. I have examined this assemblage, and it must be placed in the same division as the assemblage from the Grassy Creek shale.

CORRELATION OF THE LOUISIANA WITH THE BURLINGTON SECTION

Weller (1905) correlated part of the Louisiana with the English River and McCraney units of Iowa because of lithologic resemblance and the occurrence of *Paraphorhynchus striatocostatum* (Meek and Worthen) in each.

Moore (1928) rejected Weller's correlation citing the presence of five or six species in the McCraney limestone at Burlington that do not occur in the Louisiana limestone. He correlated the English River with the Hannibal formation of Missouri. As the Hannibal overlies the Louisiana, and the McCraney overlies the English River, Moore's correlation recognizes the incongruity of correlating the McCraney with the Louisiana.

Laudon (1929) correlated the English River with the Hannibal shale rather than with part of the Louisiana, and correlated the McCraney with the Chouteau of Missouri.

Williams (1943) stated that if the English River "is equivalent to the Hannibal, then beds above them will be as young as or younger than the Hannibal and consequently younger than the Louisiana." His study of the Louisiana fauna influenced him to believe that the Louisiana is older than the English River member. He indicated, as did Weller, that the McCraney has a fauna, "more like those of the Louisiana limestone than like the Hannibal. Units 2 and 4 (English River and Prospect Hill) have faunas that seem to match those of the Hannibal more closely than those of the Louisiana."

He concluded that the Louisiana was probably equivalent of a zone between the Maple Mill and English River members of Iowa.

Grohskopf, Hinche, and Greene (1939) show that the Louisiana limestone thins both to the north and south of its type area. The limestone forms a large lens in a shale mass that does not extend to the northern boundary of Missouri.

Conodont assemblages indicate a similar age for the English River and Prospect Hill units of Iowa, and the Bushberg and Hannibal formations of Missouri. The McCraney limestone, lying between the English River and Prospect Hill members did not produce a conodont assemblage, but because of its position its age must correspond to the English River and Prospect Hill siltstones. The similarity of the conodont assemblages of the Grassy Creek, Louisiana, and the Maple Mill precludes any correlation between the McCraney and the Louisiana limestones.

CONCLUSIONS

The lack of agreement as to what constitutes a Devonian or Mississippian conodont assemblage is summarized by Cooper (see Weller et. al. 1948). The Maple Mill assemblage is closely related to the Grassy Creek, Chattannoga, New Albany, Woodford, Genundewa, and Ohio shales and is here assigned to the Upper Devonian.

Well sections through southern Iowa and northern Missouri indicate that the Maple Mill shale grades laterally into the Grassy Creek shale of Missouri, and for that reason the two are considered time equivalents or even synonymous.

The conodont assemblages of the English River and Prospect Hill siltstones of Iowa are Lower Mississippian. The assemblages of these siltstones are very similar,

but *Siphonodella quadruplicata* (Branson and Mehl) is the dominant species in the English River, whereas *Siphonodella duplicata* (Branson and Mehl) is the dominant species in the Prospect Hill siltstone. The assemblages are closely related to the Bushberg-Hannibal assemblages in Missouri.

Examination of well sections through southern Iowa and northern Missouri reveals that the Hannibal grades laterally into the English River and Prospect Hill members of Iowa. The evidence indicates that the English River, Prospect Hill, and Bushberg-Hannibal units are time equivalents.

The Louisiana limestone of Missouri is not present in the Iowa Devonian-Mississippian section, and the Louisiana limestone cannot be correlated with the McCraney limestone of Iowa.

SECTIONS AND COLLECTING LOCALITIES

The following sections expose the most complete stratigraphic succession and yielded the figured specimens for this paper.

Des Moines County

Locality 1. Exposures at Prospect Hill, city of Burlington, extending from the yards of the Burlington railway south to Crapo Park. A generalized section is given under "Historical Summary".

Locality 2. Exposures along Main Street at North Hill, city of Burlington. The succession involves the same beds as at Prospect Hill.

Locality 3. Exposures in the bluff of the Mississippi River, NW¼ sec. 2, T. 70 N., R. 2 W. The English River and superjacent beds are exposed.

Louisa County

Locality 4. Section in the Mississippi River bluffs in the second creek north of the county line in the E½ sec. 34, T. 73., R. 2 W. (Modified from Udden).

		Feet
(Wassonville)	Limestone, yellow rather fine grained crinoidal, broken with joints in upper part	10
(North Hill)	Limestone, oölitic	3
(Prospect Hill)	Siltstone, yellow	2
(McCraney)	Limestone, yellow or rusty brown, compact	3
(English River)	Siltstone, blue, weathered yellow, with teeth of *Helodus* and molds of brachiopods in upper part	9

Locality 5. Section in a creek 1 mile southeast of Elrick Junction in the south part of sec. 29, T. 73 N., R. 2 W. (Modified from Udden).

		Feet
(North Hill)	Limestone, yellow, exhibiting oölitic structure	10
(Prospect Hill)	Siltstone, blue, argillaceous	2
(McCraney)	Limestone, fine grained, concretionary, yellow or brown	4
(English River)	Siltstone, blue, soft, with wavy yellow stained bands, containing *Chonopectus fischeri*	8½

Locality 6. Section in and near Anderson's quarry on the east bank of Smith Creek, west of the center of the SW¼ sec. 29, T. 73 N., R. 2 W. (Modified from Udden).

		Feet
(Wassonville)	Limestone, yellow to brown, dolomitic; with geode cavities lined with calcite	6
(North Hill)	Limestone, light gray, oölitic	3
(Prospect Hill)	Siltstone, ash colored, fine grained	3
(McCraney)	Limestone, irregularly bedded, brown	3
(English River)	Siltstone, ash colored	9
(Maple Mill)	Shale, blue; progressively more calcareous below; with a carbonaceous seam about 8 inches thick near middle. Exposed in east bank of the creek north of quarry	20

Locality 7. Section exposed in the east bank of Smith Cr eek near the bridge in the NW¼ sec. 31 T. 73 N., R. 2 W. (Modified from Udden).

		Feet
(Wassonville)	Limestone, brown, soft, dolomitic	6
(North Hill)	Limestone, light gray, oölitic	2½
(Prospect Hill)	Siltstone, blue, with a thin seam of shale near the middle	3½
(McCraney)	Limestone, dark gray, fine grained, imperfectly dolomitized, exposed	1½

Locality 8. Section in a small tributary of Long Creek, south of the center of the SE¼ sec. 13, T. 74 N., R. 5 W. (Modified from Udden).

		Feet
(Wassonville)	Limestone, brown to gray, compact	8
(English River)	Siltstone, blue, soft, with molds of fossils	4
(Maple Mill)	Shale, seen farther east	7

Locality 9. Section in the west bank of Long Creek one-fourth mile south of the mouth of Johnny Creek, near the center of the south line of sec. 12, T. 74 N., R. 5 W. (Modified from Udden).

		Feet
(Wassonville)	Limestone, gray compact	8
Concealed		13
(English River)	Siltstone, brown gray and blue, soft, with molds of fossils	6
(Maple Mill)	Shale, blue, soft	12

Locality 10. North center sec. 13, T. 74 N., R. 5 W. Section similar to that given above.

Washington County

Locality 11. Section at Maple Mill in the south bank of the English River, a short distance south of the center of sec. 8, T. 77 N., R. 8 W. This is the type locality of the English River and Maple Mill units. The section has been given under "Historical Summary".

Locality 12. Section at Wassonville Mill in the south bank of the English River, in the center west line sec. 7, T. 77 N., R. 8 W. This is the type locality of the Wassonville limestone. (Modified from Van Tuyl).

		Feet
(Wassonville)	Limestone, soft, yellowish, showing fine, close stratification on weathered surface; dolomitic; interbedded chert in the form of lenses and nodules	30
(English River)	Siltstone, ash colored; exposed	4

Locality 13. Section exposed in old clay pit 1 mile south of the town of Kalona, SE¼ sec. 18, T. 77 N., R. 7 W. (Modified from Van Tuyl).

		Feet
(Wassonville)	Limestone, brown, arenaceous, dolomitic	10
(English River)	Siltstone, blue	6
(Maple Mill)	Shale blue, blocky; exposed	4

Locality 14. Section exposed in a road cut in the south center SW¼ sec. 17, T. 77 N., R. 7 W. The section is similar to the one above. Maple Mill shale exposed is about 20 feet thick.

DESCRIPTION OF SPECIES

Suborder CONODONTIFORMES Branson and Mehl

Family GNATHODONTIDAE Branson and Mehl

Genus *Icriodus* Branson and Mehl

Icriodus constrictus Thomas, n. sp.

(Pl. 1, fig. 25)

Unit deep; in direct oral view, anterior end sharp, widening regularly to truncated posterior end; crossed by 6 thin ridges that widen and bifurcate to form irregularly crenulate margins; a central thin ridge extends from end to end of unit. Oral surface ornamentation is distinctive. Aboral surface widens and deepens to a pit at posterior end; margins thick; pit incomplete in holotype.

Lacks the discrete denticles on anterior and posterior ends, the reduced number of denticles in median row, and has a more complex ornamented oral surface than *I. iowaensis* Youngquist and Peterson.

OCCURRENCE: Maple Mill shale, loc. 13.

HOLOTYPE: University of Missouri, C.831-2.

Genus *Gnathodus* Pander

Gnathodus sp. indet.

(Pl. 3, fig. 24)

Recorded from the English River is a single small specimen, and its identification is doubtful. Features suggest *G. roundyi* Gunnell, but that species has not been recorded from beds older than Lower Pennsylvanian.

OCCURRENCE: English River siltstone, loc. 5.

FIGURED SPECIMEN: University of Missouri, C.812-4.

Family POLYGNATHIDAE Ulrich and Bassler

Genus *Ancyrognathus* Branson and Mehl

Ancyrognathus minuta Thomas, n. sp.

(Pl. 1, fig. 20)

Plate thin and subrectangular; posterior one-third flat, plate like; anteriorly edges are upturned becoming almost vertical at end, forming a deep median concavity. Carinae extend almost to extremities of posterior lobes; carinae composed of small coalesced nodes which increase in size toward anterior end, but nowhere rise above upturned lateral margins of plate. Surface ornamentation consists of small nodes that pass into coalesced denticles of upturned anterior margins. Aboral surface longitudinally convex; keel small; apical pit small, and located near anterior end.

Sub-rectangular outline and nearly straight posterior edge readily distinguish this species from any species described previously.

OCCURRENCE. Maple Mill shale, loc. 13.

HOLOTYPE: University of Missouri, C.833-1.

Genus *Palmatolepis* Ulrich and Bassler

Palmatolepis ? irregularis Thomas, n. sp.

(Pl. 2, fig. 27)

Plate of medium thickness, slightly twisted and asymmetrical; margins evenly convex with slight sinuosites; inner margin transversely convex; outer margin low through mid-length, but elevated at

extremities. Carina low, originates in posterior one-third of plate, low until near azygous node at mid-length, then rises rapidly to high blade that terminates in 2 large laterally compressed denticles. Two median grooves bound blade and extend to azygous node. A shallow groove extends from azygous node to point of posterior end. Surface ornamentation consists of small nodes at anterior end. Aboral surface smooth; keel sharp, highest near extremities; apical pit small, located near anterior end of plate.

Carina does not extend full length of plate, therefore the generic reference might be questioned. Because an azygous node is present I have referred this specimen to the genus.

OCCURRENCE: Maple Mill shale, loc. 14.

HOLOTYPE: University of Missouri, C.830-5.

Genus *Polygnathus* Hinde

Polygnathus concava Thomas, n. sp.

(Pl. 3, fig. 44)

Unit plate like, subsymmetrical, arched; surface nearly flat in posterior one-third; margins irregular, but elevated to form a saucer-shaped depression in anterior two-thirds; deep depressions bound blade on anterior end. Surface ornamented by several coarse posteriorly directed ridges, which in posterior one-half reach carina; in anterior one-half ridges are nearly restricted to outer parts of plate. Carina low, composed of coalesced nodes. Aboral surface smooth; keel narrow, high at extremities; apical pit small, slitlike, located anterior to mid-length.

Species has some general characteristics of *P. papillata* and *P. verrucosa* Youngquist and Peterson.

Broad saucer-shaped depression on oral surface differentiates this species from *P. verrucosa* Youngquist and Peterson. Oral depression and stronger oral ridges distinguishes this species from *P. papillata* Youngquist and Peterson.

OCCURRENCE: English River siltstone, loc. 2.

HOLOTYPE: University of Missouri, C.821-3.

Polygnathus gigantea Thomas, n. sp.

(Pl. 3, fig. 40)

Plate thick, narrow, long, slightly curved inward, subsymmetrical; margins upturned to form moderate median depressions; anterior outer depression deeper than that which bounds blade on inner side. Oral platform ornamented by 6–9 coarse ridges in posterior half; anterior half unornamented, and only a faint expression of nodes on the upturned lateral margins. Carina high in posterior one third, composed of about 6 peglike denticles with free apices; in front of peglike denticles other denticles coalesce to form a continuous low ridge that passes onto higher blade. Blade composed of 6 or 7 compressed, fused denticles. Aboral surface convex upward, keel strong at extremities; apical pit shallow, broad, asymmetrical, elongate, margins slightly thickened, grooves extend a short distance along keel.

Oral surface division into a posterior coarsely ridged and an anterior nonornamented surface distinguishes this species from *P. longipostica* Branson and Mehl.

OCCURRENCE: Prospect Hill siltstone, loc. 2.

HOLOTYPE: University of Missouri, C.819-1.

Polygnathus ? millensis Thomas, n. sp.

(Pl. 1, fig. 32)

Plate thick, asymmetrical, sharply pointed, axis slightly curved laterally; platform expands rapidly from sharp posterior end to mid-length then tapers gradually to narrow, square anterior end; posterior margin of platform downarched, marked by irregular depressions and elevations. Carina low, slightly bifurcating at posterior end, rising gradually to an azygous node near mid-length, forward low and passing into blade; blade composed of about 6 laterally compressed denticles that do not rise much above free margins of platform. Aboral surface smooth; keel small, strong at posterior extremity, nonbifurcating; surface convex; attachment pit small, slitlike, and confined to keel.

This is one of numerous specimens from the Maple Mill shale not clearly referable to any one

genus. Azygous node is a feature restricted to *Palmatolepis*. Posterior bifurcating carina is a feature of *Ancyrognathus*, but bifurcation is not present on aboral surface of this specimen. Other features are those of *Polygnathus*.

OCCURRENCE: Maple Mill shale, loc. 13.

HOLOTYPE: University of Missouri, C.826-2.

Polygnathus nodosa Thomas, n. sp.

(Pl. 3, fig. 43)

Plate thin, highly arched, tongue shaped, transversely convex to flat except near anterior margin where 2 small depressions occur near carina. Carina low, composed of numerous small coalesced nodes; blade low, composed of completely coalesced nodes. Surface ornamented by numerous small nodes and disconnected ridges that become coarser near anterior end. Aboral surface smooth, convex upward; keel sharp, thin, strong at extremities; apical pit small, circular, located at apex of arch near anterior end.

Species is thinner, longer, more acutely pointed, and more coarsely ridged than *P. granulosa* Branson and Mehl.

OCCURRENCE: English River siltstone, loc. 5.

HOLOTYPE: University of Missouri, C.806-2.

Polygnathus orthoconstricta Thomas, n. sp.

(Pl. 3, fig. 5)

Plate thin, slightly arched, asymmetrical, curved laterally, about twice as long as wide; outer margin upturned, straight to near posterior end where edge makes a 90-degree angle to unite with carina; ornamentation consists of 7 rather indistinct ridges that fail to reach carina. Inner margin upturned more than outer margin; widest just back of anterior end and tapering evenly to posterior tip; ornamentation consists of 8 ridges of varying size that fail to reach carina, free margins nodose. Carina low, narrow, and of regular height from anterior to posterior ends; edged with short, rounded to sharp nodes, those of posterior end semidistinct, those of anterior part scarcely evident. Blade thin, length and depth about equal, rounding from its lower anterior corner through high point at mid-third down into carina without break; edged with about 4 denticles, the 2 of mid-length largest, pointed, and laterally flattened. Aboral surface smooth with large thick-lipped pit near anterior end of plate, small median groove extends forward and backward a short distance from pit.

In large apical pit, this form resembles *Pseudopolygnathus*.

Nearly straight axis and outer lateral margin, thin plate, slightly upturned margins, fainter but broader ornamentation, and more sharply constricted posterior edge differentiates this species from *P. lobata* Branson and Mehl.

OCCURRENCE: Prospect Hill siltstone, loc. 2.

HOLOTYPE: University of Missouri, C.819-4.

Polygnathus perplexa ? Thomas, n. sp.

(Pl. 2, fig. 23)

Plate thick, arrow shaped. In oral view, posterior two thirds of plate transversely convex; ornamented with small granules; margins of anterior one third sharply upturned to form shallow trenches between the free margins and the carina; free margins composed of 3 or 4 laterally compressed, coalesced, large denticles. Carina strong, rises gradually from posterior extremity to mid-length, thence straight to anterior end where it passes onto the high blade; blade composed of 4 large, coalesced, laterally compressed denticles. Aboral edge arched; margins directed orally; keel strong; attachment scar mid-length on thin keel.

There is great variation in surface ornamentation among polygnathids of this type and some uncertainty in identification. Arrangement of nodes is so variable that its value as a specific character is doubtful. Realizing the uncertainty of specific identification by the surface ornamentation I have questionably differentiated this species from *P. rhomboidea* Ulrich and Bassler because of the absence of longitudinal rows of coarse nodes on the anterior end of my species.

OCCURRENCE: Maple Mill shale, loc. 14.

HOLOTYPE: University of Missouri, C.827-3.

Polygnathus sp. A.

(Pl. 2, figs. 22, 25)

Figured specimens represent several small polygnathids that appear to be intermediate between a form in which median depression of oral surface extends to posterior end, and *Polygnathus semicostata* Branson and Mehl.

These forms grade one into the other so completely that specific division is next to impossible.

OCCURRENCE: Maple Mill shale, loc. 14.

FIGURED SPECIMENS: University of Missouri, C.827-4.

Polygnathus sp. B.

(Pl. 3, fig. 33)

Oral view of one of an immature and variable group of specimens. Form common in Lower Mississippian units.

OCCURRENCE: English River siltstone, all localities.
Prospect Hill siltstone, all localities.

FIGURED SPECIMEN: University of Missouri, C.818-3.

Polygnathus sp. C.

(Pl. 3, fig. 34)

Plate small and thin, nearly bilaterally symmetrical, twice as long as thick, strongly down-turned at acute posterior end. Oral surface beveled inward slightly to carina, ornamented with narrow ridges, normal to margins and extending from margins nearly to carina. Carina nearly straight, made up of distinct denticles, back ones longest, others decreasing in height to middle of plate, thence increasing again to union with higher blade. Keel high and sharp at extremities, low and flat through mid-length, a relatively large pit occurs near anterior end; from pit a narrow groove extends backward along keel.

Large pit resembles navel of *Pseudopolygnathus*.

OCCURRENCE: English River siltstone, loc. 12.

FIGURED SPECIMEN: University of Missouri, C.813-3.

Genus *Polylophodonta* Branson and Mehl

Polylophodonta acuta ? Thomas n. sp.

(Pl. 1, fig. 31)

Plate moderately thick, tongue shaped, margins slightly lobed. Posterior half of oral surface flat, anterior half irregularly convex passing into concave anterior to mid-length; outer anterior margin bowed downward; inner anterior margin high. Oral surface ornamented by low, short, disconnected ridges not arranged in any regular pattern. Carina sigmoid, extends full length of plate; consists of low coalesced nodes; rises sharply to pointed blade; anterior edge of blade curved so as to unite with aboral edge of keel with a smooth junction. Aboral surface marked by irregular depressions and elevations; keel narrow, high at extremities; apical pit small, slitlike, confined to keel, located slightly forward of mid-length.

P. rugosa Branson and Mehl does not have a carina extending length of plate.

Maple Mill species is flatter and more plate-like than *P. concentricus* (Ulrich and Bassler). The variation ascribed to *P. concentricus* may conceivably be broad enough to include the Maple Mill species.

OCCURRENCE: Maple Mill shale, loc. 13.

HOLOTYPE: University of Missouri, C.825-2.

Family PRIONIODIDAE Ulrich and Bassler

Genus *Centrognathodus* Branson and Mehl

Centrognathodus dubius Thomas, n. sp.

(Pl. 4, fig. 3)

Posterior limb blade-like, deepest near posterior end, regularly arched, moderately straight through posterior half, regularly flexed inward through anterior half, with more pronounced flexure of inner anterior blade. Outer spur not developed, but indicated by an offset at origin of inward flexure, outside of general line of bar denticles. Bar denticles about 7, anterior ones circular in cross section; 3 larger denticles at back end of bar, discrete, laterally compressed, all inclined posteriorly. Denticles on inward flexure, circular in cross section, 6 smaller than those of posterior bar, discrete, but closely crowded. Aboral edge sharp; apical pit small, circular, located at anterior end of apical denticle.

Although this species lacks the typical outer spur of the genus it agrees in all other details, and I do not hesitate to place it in the genus. This specimen is stratigraphically out of place as it has not been recorded in sediments younger than Devonian. Evidence of admixture was not evident in the Prospect Hill siltstone, and why this single specimen should be found in such a good state of preservation is not readily explained.

OCCURRENCE: Prospect Hill siltstone, loc. 2.

HOLOTYPE: University of Missouri, C.817-4.

Genus *Diplododella* Ulrich and Bassler

Diplododella sp. A.

(Pl. 1, fig. 21)

Arch high; oral outline in posterior view nearly straight; aboral outline with sharp apex, limbs forming an angle of about 90 degrees at their union. Limbs straight, but directed forward from their union beneath apical denticle; moderately thin and deep. Major denticles of each limb about 7, slender, circular in cross section, widely separated on posterior side of blade. Lesser denticles very small, slender, circular in section, one alternating in position with each major denticle. Germ denticles evident to near base of blade, all of which have an oral termination. Apical denticle large, circular. Posterior bar broken. Aboral edge of blade sharp, terminating in a small elongate pit at apex of unit.

OCCURRENCE: Maple Mill shale, loc. 13.

FIGURED SPECIMEN: University of Missouri, C.830-3.

Diplododella ? sp.

(Pl. 3, fig. 29)

A single bar of uniform depth and a thickness decreasing from nearly as great as depth at one end (broken) to thin at the other seems to represent one limb of arch of a diplododellid of distinctive features.

Similar type bars occur in the Maple Mill and Grassy Creek shales.

OCCURRENCE: English River siltstone, loc. 4.

FIGURED SPECIMEN: University of Missouri, C.815-4.

Genus *Euprioniodina* Ulrich and Bassler

Euprioniodina iowaensis Thomas, n. sp.

(Pl. 1, fig. 8)

Bar flexed inward, slightly arched, thickest at oral edge forming a moderate offset to denticles on inner side; tapers rapidly to thin aboral edge. Denticles sub-circular, 11 or more, united above oral edge of bar, but with free apices; evident as germ denticles to near base of bar. Apical denticle large, compressed, sharp fore and aft edges, base of inner margin thickened to overhang pit; outer margin concave. Aboral projection short, thick, tapers rapidly to sharp point; 4 small fused denticles with free compressed apices are present on anterior edge of aboral projection. Apical pit small, circular, extends to near extremity of aboral projection as a faint groove.

OCCURRENCE: Maple Mill shale, loc. 14.

HOLOTYPE: University of Missouri, C.830-4.

Euprioniodina lateralis Thomas, n. sp.

(Pl. 1, fig. 9)

Aboral edge of bar straight in direct lateral view; oral edge gently convex. Bar thickest at mid-length; lower margin beveled to produce sharp aboral edge. Denticles subcircular, discrete, 11, evi-

dent as germ denticles to near base of bar, and composed of 2 or 3 germ denticles that do not reach surface of bar. Major fang and process offset inward from a medial line of bar, large, compressed with flattened outer side and rounded inner face; swollen on inner base to form small projection over pit. Aboral projection barlike, about one fourth as long as main bar; 4 small fused denticles with free apices are present on anterior edge of aboral projection. Apical pit small, elongate, extending a short distance along process as a small groove.

Offset terminal fang and barlike aboral projection with discrete denticles distinguishes species from *E. iowaensis*.

OCCURRENCE: Maple Mill shale, loc. 14.

HOLOTYPE: University of Missouri, C.829-3.

Euprioniodina symmetrica Thomas, n. sp.

(Pl. 4, fig. 37)

Main bar biconvex, deeper than thick, slightly incurved. Aboral edge sharp with a faint median groove extending most of length of bar and ending anteriorly in an obscure circular pit beneath inwardly swollen base of anterior point or arch apex. Denticles of main bar compressed, with sharp edges in close contact to near their apices; subequal in size; total number probably more than ten; base of denticles confluent with outer lateral side of bar, inner side shows a distinct offset between denticles and bar. Main denticle large, laterally compressed, lateral faces equally rounded, posteriorly and anteriorly keeled, curved inward, base of inner side produced to form a triangular projection, outer side concave. Antero-inferior process pick shaped, aboral edge sharp, medially grooved. Denticles of small bar irregular in size, but otherwise similar to those of main bar, increasing in size and height to base of main denticle.

The massive bars and their angle of divergence distinguishes this from all other species of the genus.

OCCURRENCE: English River siltstone, loc. 11.

HOLOTYPE: University of Missouri, C.815-2.

Euprioniodina sp. A.

(Pl. 3, fig. 23)

Barlike; depth width ratio about equal; regularly arched; flexed slightly inward. Denticles of main bar about 5; crowded; laterally compressed. Apical denticle about twice as large as bar denticles; strongly curved posteriorly. Denticles of posterior bar similar to others but smaller, bar broken. Aboral edge flat; apical pit deep, circular, extending along flattened sides a short distance as a groove.

OCCURRENCE: English River siltstone, loc. 12.

FIGURED SPECIMEN: University of Missouri, C.806-5.

Genus *Hibbardella* Ulrich and Bassler

Hibbardella longipostica Thomas, n. sp.

(Pl. 1, fig. 16)

Anterior bar slightly arched, slightly deeper than thick; aboral edge sharp; oral edge truncated; main bar curved posteriorly; denticles circular in cross-section, discrete. Posterior bar long, tapers to a spatula terminus; denticles circular in section on anterior end, but pass to laterally compressed on posterior end; posteriorly inclined, 10 in number, discrete; in transmitted light, 2 or 3 suppressed germ denticles are evident between large denticles, and give illusion of a hindeodellid bar, these small denticles do not have oral edge terminations; bar similar to anterior arch. Apical denticle circular in section; outer end missing in the holotype.

Coarse denticles that increase in size posteriorly, spatula terminus, and greater length of posterior bar as compared to anterior bars are diagnostic features of this species.

OCCURRENCE: Maple Mill shale, loc. 13.

HOLOTYPE: University of Missouri, C.825-1.

Hibbardella macrodentata Thomas, n. sp.

(Pl. 4, fig. 25)

Limbs of unit barlike, slightly more than twice as deep as thick, curved inward, 1 limb broken. Denticles discrete, large, circular. Fang curved, large, laterally compressed, twisted toward its apex. Posterior process blunt, nondenticulate. Aboral edge of unit sharp; apical pit small, extending only a short distance along processes as a groove. Completely suppressed germ denticles seen in transmitted light are located between the bar denticles.

If suppressed small germ denticles alternating in position with the major denticles were continued to oral terminations the form should be classified as *Diplododella*.

The following characteristics readily differentiate it from *H. angulata* (Hinde): Main denticle recurved and without median longitudinal groove, limb denticles large and circular in cross section.

OCCURRENCE: English River siltstone, loc. 12.

HOLOTYPE: University of Missouri, C.820-5.

Hibbardella plana Thomas, n. sp.

(Pl. 2, fig. 28)

Anterior arch blade-like, straight, deep, limbs equal. Oral surface in lateral view irregularly convex; limb denticles 5 or 6, slightly compressed, sub-equal in size and length, but shorter near extremities; deeply inserted; visible as germ denticles to aboral edge; united to near free apices; without any regular pattern as some denticles are slightly curved forward, some backward. Apical denticle broken, laterally compressed. Posterior process broken. Aboral edge sharp, thin; apical pit not present.

Deep, thin blade limbs readily distinguish this from any species described previously.

OCCURRENCE: Maple Mill shale, loc. 13.

HOLOTYPE: University of Missouri, C.827-5.

Hibbardella recurvata Thomas, n. sp.

(Pl. 2, fig. 3)

Anterior arch aborted, blade-like; 1 limb offset and higher than the other; 1 laterally compressed denticle on each limb. Posterior extremity slightly barlike; oral and aboral edges sharp; denticles laterally compressed, 3 preserved. Terminal fang large, recurved, laterally compressed with sharp anterior and posterior ridges. Apical pit small, elongate.

OCCURRENCE: Maple Mill shale, loc. 13.

HOLOTYPE: University of Missouri, C.824-4.

Hibbardella sp. A.

(Pl. 4, fig. 31)

Anterior arch barlike, broken, directed slightly downward and outward from base of fang; denticulation not evident. Apical denticle long, slender, compressed to produce moderately sharp anterior and posterior edges that are twisted in a slight spiral. Posterior bar short, straight, rapidly tapered to a blunt point, slightly compressed; 2 small nodes occur near extreme end. Apical pit small, elongate; radiating from pit are small grooves that extend to extremities of bars.

OCCURRENCE: Prospect Hill siltstone, loc. 11.

FIGURED SPECIMEN: University of Missouri, C.818-2.

Genus *Hindeodella* Ulrich and Bassler

Hindeodella sp. indet.

(Pl. 4, fig. 2)

Unit blade-like, only slightly curved laterally. Aboral edge straight and sharp in direct lateral view; oral edge convex with greatest thickness at mid-length. Anterior end incomplete, posterior end spatula-like. Major group of blade denticles subcircular in section, separated by variable distances, all inclined posteriorly; between each pair are 2–6 small germ denticles, very few of which project above oral edge of blade.

The Bushberg formation of Missouri has similar specimens that illustrate a tendency toward a blade-like, rather than a bar development.

OCCURRENCE: Prospect Hill siltstone, loc. 2.
FIGURED SPECIMEN: University of Missouri, C.818-4.

Hindeodella sp. A.

(Pl. 4, fig. 1)

Bar short and massive; nearly straight laterally; slightly wider than deep through mid-length; back end bearing 2 laterally flattened, short blunt denticles, lower about on level of aboral edge of bar; second denticle from posterior end broken, largest of all and strongly recurved; inner anterior flexure unknown. Fang large, blunt, laterally compressed yet conical. Major and minor denticles variable as to size and relation to each other; laterally compressed, confluent to near their apices. Aboral edge flattened, marked by a small slitlike pit extending a short distance along bar.

OCCURRENCE: Prospect Hill siltstone, loc. 2.
FIGURED SPECIMEN: University of Missouri, C.809-4.

Hindeodella ? sp.

(Pl. 1, fig. 12)

Unit blade-like; sigmoid, arched. Antero-inferior process flexed inward and downward. Aboral edge moderately sharp; a faint median groove extending to near extremities from a small circular apical pit located at main flexure. Denticles subcircular at anterior end becoming laterally compressed toward posterior end. Major denticles 2, posterior larger; minor denticles 3, similar to others but smaller Germ denticles evident to near base of unit, all end in an oral projection.

OCCURRENCE: Maple Mill shale, loc. 13.
FIGURED SPECIMEN: University of Missouri, C.833-2.

Genus *Ligonodina* Ulrich and Bassler

Ligonodina dubia Thomas, n. sp.

(Pl. 4, figs. 23, 24)

Base barlike, subrounded; both limbs of arch nearly straight with a sharp lateral flexure at apex; posterior limb carrying apical denticle; denticles of anterior limb 2; slightly compressed with a faint ridge on anterior and posterior sides; denticles well separated, recurved, slightly larger than those of posterior limb. Apical denticle much longer, and about twice diameter of limb denticles, slightly recurved, compressed with faint anterior and posterior ridges, posterior ridge passes into a faint depression at base of fang. Denticles of posterior limb 2; smaller but similar to those of anterior limb. Aboral surface of limbs flattened, grooved with a small excavation beneath apical denticle.

OCCURRENCE: Prospect Hill siltstone, loc. 2.
SYNTYPES: University of Missouri, C.810-2.

Ligonodina gigantea Thomas, n. sp.

(Pl. 4, fig. 33)

Terminal fang large, exceptionally long and straight, recurved and circular in cross section at base, laterally compressed, with sharp antero-posterior ridges through its terminal two thirds. Antero-inferior process aborted, massive, directed downward, inward, and backward; nondenticulate. Posterior bar blunt, massive; 1 large denticle at posterior extremity. Aboral edge of unit with posteriorly directed narrow groove beneath apical denticle.

OCCURRENCE: Prospect Hill siltstone, loc. 2.
HOLOTYPE: University of Missouri, C.810-1.

Ligonodina minuta Thomas, n. sp.

(Pl. 3, fig. 27)

Bars blade-like, short, regularly curved laterally, thickened at apical denticle, but thickening is mainly due to flaring apron developed on base of apical denticle. Limbs bear separated, laterally flattened, sharp-edged, blunt denticles that increase in size toward apical denticle. Apical denticle large, rounded, sharply flexed inward and backward. Pit asymmetrically conical, with a thin flared apron; shallow grooves extend from pit along limbs to near extremities.

OCCURRENCE: English River siltstone, loc. 12.
HOLOTYPE: University of Missouri, C.815-5.

Ligonodina sp. A.

(Pl. 2, fig. 1)

Terminal fang large, recurved, broken, subcircular in section, anterior and posterior edges bear small ridges that connect with the processes. Antero-inferior process comparatively stout, recurved, and directed sharply downward so that its aboral edge lies about in the same plane as the main bar. Denticles of antero-inferior bar 4, discrete, circular in section. Posterior bar deeper than wide, broken, aboral edge sharp, denticles at least 5, circular in section, directed posteriorly, subequal in size. Pit small, slitlike, located near junction of bars.

OCCURRENCE: Maple Mill shale, loc. 13.
FIGURED SPECIMEN: University of Missouri, C.830-1.

Genus *Pelekysgnathus* Thomas, n. gen.

Dental unit composed of a thin, moderately deep blade that is straight to slightly arched in lateral view. Oral surface of blade marked by low, discrete or fused, node or ridge denticles that are not evident as germ denticles within blade. Posterior end of blade consists of a major thornlike denticle that is directed posteriorly at varying degrees. Aboral surface symmetrically excavated entire length; pit deepest beneath major fang. Thin lips project downward to cover aboral excavation.

Generic relations of this group doubtful. Aboral excavation and cross-ridges on oral surface of one species suggests a relationship to *Icriodus*. Major fang at end of a blade suggests *Prioniodus*.

GENOTYPE: *Pelekysgnathus inclinata* Thomas.

Pelekysgnathus communis Thomas, n. sp.

(Pl. 2, figs. 6, 7, 8)

Blade short, depth-length ratio about equal, straight to slightly curved laterally, deepest at anterior end. Denticles of blade at least 3, laterally compressed and coalesced so as to form an irregular oral surface; germ denticles not evident in blade. Major fang thornlike, laterally compressed, directed posteriorly about 45 degrees from vertical, about twice as long as depth of blade. Aboral surface with a symmetrical expanding excavation extending from anterior to posterior, deepest beneath fang. Thin lips project downward to cover excavation, but flare over the main pit. Apical pit symmetrical.

OCCURRENCE: Maple Mill shale, loc. 14.
SYNTYPES: University of Missouri, C.831-3.

Pelekysgnathus costata Thomas, n. sp.

(Pl. 2, fig. 9)

Blade moderately deep, slightly thickened toward posterior end so as to unite evenly with posterior denticle; down arched and flexed inward in direct lateral view; oral surface slightly convex with posterior denticle inclined in a line with this surface. Oral surface marked by 4 low nodes on anterior end followed by 3 short cross ridges composed of 2 fused denticles, ridges followed by 2 small nodes which if coalesced would form a fourth ridge; germ denticles not evident in blade. Major denticle compressed with sharp oral and aboral edges. Aboral surface excavated by a symmetrically expanding pit.

OCCURRENCE: Maple Mill shale, loc. 2.
HOLOTYPE: University of Missouri, C.831-4.

Pelekysgnathus inclinata Thomas, n. sp.

(Pl. 2, fig. 10)

Blade slightly curved, arched, deepest at anterior end. Denticles laterally compressed, short, discrete, but becoming reduced and fused toward posterior fang with 1 denticle united to fang; germ denticles not evident in blade. Posterior fang inclined about 45 degrees; laterally compressed with sharp anterior and posterior edges. Aboral excavation expanding gradually from anterior to pos-

terior ends. Lateral lips flared beneath fang to cover an elongate, symmetrical pit. Pit deepest beneath fang.

OCCURRENCE: Maple Mill shale, loc. 14.

GENOTYPE: University of Missouri, C.834-4.

Pelekysgnathus nodosa Thomas, n. sp.

(Pl. 2, fig. 5)

Blade nearly straight laterally; arched, thin; 4 equal discrete node-like denticles rise a short distance above oral edge; germ denticles not evident in blade. Posterior denticle thornlike, about twice as long as blade depth; laterally compressed with sharp anterior and posterior edges; directed posteriorly about 35 degrees from vertical. Aboral side symmetrically excavated throughout length; thin lips cover excavation, becoming more flared beneath fang. Pit expanded beneath major denticle.

OCCURRENCE: Maple Mill shale, loc. 14.

HOLOTYPE: University of Missouri, C.831-5.

Genus *Trichonodella* Branson and Mehl

Trichonodella sp.?

(Pl. 4, fig. 32)

Anterior arch aborted, limbs very short, ends missing, rodlike, approximating short processes directed downward and laterally from postero-lateral side of flared base of fang; denticles minute or lacking. Fang slender, long, subcircular at base becoming oval near apex, slightly recurved. Posterior bar short, end missing, wider than deep anteriorly, rapidly tapering to a point, denticles small or lacking. Aboral surface of unit excavated beneath fang by a conspicuous pit which is continued along broad flat or transversely concave aboral surface of bar as a small groove.

This form seems closely related to types of same genus that occur in the Bushberg formation of Missouri.

OCCURRENCE: English River siltstone, loc. 12.

FIGURED SPECIMEN: University of Missouri, C.813-2.

Family PRIONIODINIDAE Ulrich and Bassler

Genus *Bryantodus* Ulrich and Bassler

Bryantodus lateralus Thomas, n. sp.

(Pl. 2, fig. 12)

Base moderately arched, evenly curved inward, diamond shaped at extremities, becoming triangular toward apex, inner lateral margin bears an expanding ridge-like projection. Aboral edge sharp, without evidence of a median longitudinal groove and with very minute apical pit. Posterior limb broken, but probably about same length as anterior limb. Large blunt denticle at apex of arch. Denticles of limbs about 12, thornlike or slightly compressed; fused to near apices or coalesced to form a serrate ridge; largest denticles near anterior end from which denticles decrease in size toward apical denticle; all denticles confined to outer margin, except near apex where there is a thickening of the bar.

Allied to *B. normalis* Ulrich and Bassler and *B. simplex* Branson and Mehl. Differs from first by a narrower cusp and a nodose inner ridge. Differs from latter by more limb denticles, a sharp aboral edge, and larger limb denticles with anterior few the largest.

OCCURRENCE: Maple Mill shale, loc. 13.

HOLOTYPE: University of Missouri, C.832-3.

Bryantodus millensi Thomas, n. sp.

(Pl. 2, fig. 13)

Bar moderately arched, thick, triangular in section, regularly curved inward; inner lateral margin produced into a shelflike projection that extends most of length of bar; outer margin thickened, but not produced into shelf; surface marked by small vertical ridges. Denticles of anterior bar coarse, short, subcircular in outline, closely spaced, but discrete, subequal in height and size. Denticles of

posterior limb 4, similar to anterior bar. Apical denticle large, spike-like with flattened surface developed on inner lateral margin; rounded on outer side. Aboral edge sharp; apical pit very small, located beneath apical denticle.

Differs from *B. lateralus* in having more down sweep to lateral platform and coarser limb denticles.

OCCURRENCE: Maple Mill shale, loc. 13.

HOLOTYPE: University of Missouri, C.827-2.

Bryantodus sp.?

(Pl. 2, fig. 14)

This single specimen possesses a bar that is moderately arched, flexed laterally; triangular in cross section, and the triangularity is accentuated by development of a shelflike projection through mid-length of inner lateral side; outer lateral margin thickened, but not extended. Denticles laterally compressed, offset from inner lateral side, irregular as to size and shape. Anterior limb bears at least 10 denticles; posterior limb at least 8. Apical denticle at least twice as large as limb denticles, otherwise similar. Aboral edge sharp; apical pit slitlike, small, located beneath apical denticle.

OCCURRENCE: Maple Mill shale, loc. 14.

FIGURED SPECIMEN: University of Missouri, C.826-4.

Bryantodus sp. A.

(Pl. 2, fig. 2)

Bar deep, triangular in section and truncated to produce a long facet on lower edge. Denticles long, laterally compressed, united through most of their length; germ denticles evident to near base.

OCCURRENCE: Maple Mill shale, loc. 13.

FIGURED SPECIMEN: University of Missouri, C.822-1.

Bryantodus sp.

(Pl. 2, fig. 15)

Base regularly arched, slightly curved inward with a sharper flexure at posterior end than at anterior end. Aboral edge sharp; apical pit small, slitlike, with grooves extending only a short distance along limbs. Oral edge of base swollen through mid-length producing a slight offset of denticles with lateral margins. Posterior bar shorter than anterior. At apex of arch is a large laterally compressed, posteriorly inclined major denticle. Denticles of anterior limb about 9, irregular in size, united to near their sharp apices; posterior denticles 6, similar to those of anterior limb.

Because this is a single specimen, and because of variability of limb denticles of this genus a specific name does not seem justifiable at this time.

OCCURRENCE: Maple Mill shale, loc. 13.

FIGURED SPECIMEN: University of Missouri, C.830-2.

Bryantodus sp. B.

(Pl. 4, fig. 30)

This distinctive specimen is too broken for specific identification. It has a well developed inner oral platform, and at apex of arch 2 low, orally directed nodes that do not touch the apical denticle.

OCCURRENCE: English River siltstone, loc. 11.

FIGURED SPECIMEN: University of Missouri, C.820-4.

Genus *Lonchodina* Ulrich and Bassler

Lonchodina sp. A.

(Pl. 2, fig. 4)

Base thick; arched sharply with marked lateral offset of arch just in front of apical denticle. Posterior bar blunt with inward flexed terminus; anterior bar spatula shaped with terminus flexed outward; aboral edge flat becoming rounded at extremities; a faint median groove originates in a large, shallow, round apical pit, and extends most of length of bars. Denticles of posterior bar at least 3, circular, anterior one laterally compressed, discrete. Apical denticle tear-drop in cross section, broken.

OCCURRENCE: Maple Mill shale, loc. 2.
FIGURED SPECIMEN: University of Missouri, C.829-4.

Lonchodina sp. B.

(Pl. 1, fig. 6)

Base thick except at extremities, moderately arched with a slight offset at apex. Limbs about same length, each broadly curved inward. Aboral edge flat; a small median ridge extends length of bar; apical pit small. Denticles of each limb about 6, circular, discrete, oral extremities unknown. Apical denticle large, subcircular, recurved inward and backward, broken.

OCCURRENCE: Maple Mill shale, loc. 13.
FIGURED SPECIMEN: University of Missouri, C.823-5.

Lonchodina sp. C.

(Pl. 4, fig. 14)

Unit slightly arched; sigmoid; thickened through mid-length; blade-like at extremities. Denticles of anterior limb about 6, laterally compressed with sharp anterior and posterior edges, (broken), denticles slightly larger toward extremities. Posterior limb (broken) bears about 4 denticles that are smaller than, but similar to, those of anterior limb. Aboral surface broad through mid-length; tapering to sharp edges at extremities; apical pit small, located beneath apical denticle; small grooves extend from pit a short distance along bars.

OCCURRENCE: Prospect Hill siltstone, loc. 2.
FIGURED SPECIMEN: University of Missouri, C.820-1.

Genus *Nothognathella* Branson and Mehl

Nothognathella gigantea Thomas, n. sp.

(Pl. 1, fig. 14)

Unit moderately arched; regularly curved inward. Anterior limb longer than posterior limb. Aboral keel thin, low through central portion of arch, strong at extremities. Apical pit small, located beneath major fang. Outer lateral edge thickened through central portion of arch, elsewhere denticles form an even junction with this edge. Inner margin of base barlike at anterior end, then rapidly expanded into a thin, aborally directed plate which attains its maximum width a short distance in front of major fang, thence decreasing in width to unite with posterior extremity to form a bar. Surface of plate marked by a series of irregular, discontinuous ridges. Denticles of anterior limb 4, shorter, but otherwise similar to those of anterior limb. Major fang large, thornlike, nearly circular in section, only slightly inclined posteriorly.

In original generic description, limb with greatest lateral expansion is designated as posterior and denticles are inclined in that direction. If direction of inclination of denticles is taken as posterior, greatest lateral expansion on this specimen is on anterior limb. In this respect the generic reference of this specimen might be questioned.

OCCURRENCE: Maple Mill shale, loc. 13.
HOLOTYPE: University of Missouri, C.833-5.

Nothognathella minuta Thomas, n. sp.

(Pl. 1, fig. 15)

Unit moderately arched; regularly curved inward. Anterior limb longer than posterior limb. Aboral keel thin, low through central portion of arch, strong at extremities. Apical pit small, located beneath major fang. Outer edge of arch thickened through central portion, but otherwise denticles form an even junction with this edge. Inner margin of base barlike at anterior end, thence rapidly expanded into a thin, aborally directed plate which attains its maximum width a short distance in front of major fang, thence decreasing in width to unite with posterior extremity to form a bar. Surface of plate covered by small nodes some of which extend upon major denticle as small ridges. Denticles of anterior limb 8, subcircular in section, discrete. Denticles of posterior limb 5, shorter, but otherwise similar to those of anterior limb. Major denticle large, laterally compressed, with small longitudinal striae.

Differs from *N. gigantea* by having a laterally compressed major denticle that is posteriorly inclined, and a down-swept inner margin that is covered by nodes.

OCCURRENCE: Maple Mill shale, loc. 13.

HOLOTYPE: University of Missouri, C.827-1.

Genus *Ozarkodina* Branson and Mehl

Ozarkodina millensis Thomas, n. sp.

(Pl. 2, fig. 18)

Blade deep, thin, regularly arched and flexed inward; aboral edge sharp with a very small, slitlike, sharp-edged pit just anterior to apex of arch; pit covered on outer margin by a thin lip which extends downward as a thickening of the blade. Denticles of anterior limb about 12; rising from low anterior end to subequal through midlength; germ denticles evident to near base, but do not extend as deep as those of posterior bar. Apical denticle not much larger than other denticles; offset posteriorly from apical pit. Denticles of posterior limb about 12, similar to those of anterior limb, but more inclined.

OCCURRENCE: Maple Mill shale, loc. 13.

HOLOTYPE: University of Missouri, C.829-5.

Ozarkodina sp. A.

(Pl. 3, fig. 13)

Blade thin; moderately deep; straight laterally; regularly arched. Limb denticles laterally compressed; coalesced with free sharp apices; all inclined posteriorly; about 5 on anterior bar; 7 on posterior limb; subequal in height and width; no evidence of suppressed germ denticles although origins are evident in transmitted light near aboral edge. Aboral edge sharp; apical pit conical extending along bars as aproned groove.

OCCURRENCE: Prospect Hill siltstone, loc. 2.

FIGURED SPECIMEN: University of Missouri, C.817-2.

Genus *Palmatodella* Ulrich and Bassler

Palmatodella sp. indet.

(Pl. 3, fig. 4)

A single broken specimen is the only representative of this genus found in these Lower Mississippian units.

OCCURRENCE: English River siltstone, loc. 12.

FIGURED SPECIMEN: University of Missouri, C.814-2.

Genus *Pseudopolygnathus* Branson and Mehl

Pseudopolygnathus constrictiterminata Thomas, n. sp.

(Pl. 4, fig. 16)

Plate thick, about twice as long as wide, axis slightly curved. Platforms widest at front narrowing regularly to posterior end; margins slightly upturned to form a trench between it and carina; marked by 6 or 7 low, rounded nodes, anterior pair extend from margin to carina; all others fail to reach carina. Carina low, broad, nodose. Blade massive, broken in holotype. Aboral surface smooth, keeled; navel large, margins rounded and elevated, rhomboidal with short anterior and posterior grooves extending along keel.

OCCURRENCE: English River siltstone, loc. 12.

HOLOTYPE: University of Missouri, C.807-4.

Genus *Solenodella* Branson and Mehl

Solenodella lateranodosa Thomas, n. sp.

(Pl. 3, fig. 19)

Blade straight except for a marked inward turn of lower back corner; oral edge differentiated into an apical and a pre-apical high point; front elevation consisting of 2 slightly longer and wider denticles than adjacent units, separated from the front end by about 6 denticles ranging from very short at

front to nearly length of pre-apical elevation at back. Apical denticle about two-thirds length of blade from front; between this and pre-apical elevation are about 6 subequal crenulations or denticles. Posterior denticles about 9, of subequal length except near back where they shorten markedly. Blade smooth; germ denticles evident in transmitted light through depth of blade nearly to its aboral edge, more numerous than oral edge terminations. Outer ridge, closely bordering aboral edge, extending length of blade, low in anterior third, but becoming somewhat shelflike to near posterior edge. Two small nodes are located on outermost position of this shelf at position of pit. Aboral edge sharp, slightly arched, with small pit on outside of aboral ridge, at mid-length, which continues as a narrow groove both anteriorly and posteriorly for a short distance.

S. bialata Branson and Mehl has a distinct parapet, whereas this species does not.

OCCURRENCE: English River siltstone, loc. 12.

HOLOTYPE: University of Missouri, C.813-1.

Genus *Spathognathodus* Branson and Mehl

Spathognathodus flexus Thomas, n. sp.

(Pl. 2, fig. 20)

Blade thin; in direct oral view, anterior three fourths straight, posterior one fourth flexed inward about 15 degrees. Oral outline, in direct lateral view, nearly straight through anterior three fourths, posterior one fourth dropping rapidly to a somewhat pointed end. Aboral edge, in direct lateral view, curved downward from anterior end thence straight to navel where edge is flexed downward about 15 degrees. About 24 denticles, laterally compressed, confluent to near sharp-free apices, do not extend much below mid-line; subequal in length, those of posterior limb shorter than the rest, no evidence of suppressed germ denticles. Aboral edge of blade sharp; apical pit circular with small median groove extending only a short distance along limbs; thin-lipped projections surround pit.

Moderately sharp flexure of posterior end suggests the genus *Bactrognathus*. Marked down arch and lateral offset of posterior one fourth of blade, and lack of a prominent apical denticle distinguishes this species from *S. abnormis* (Branson and Mehl).

OCCURRENCE: Maple Mill shale, loc. 14.

HOLOTYPE: University of Missouri, C.834-5.

Spathognathodus quintidentatus Thomas, n. sp.

(Pl. 4, figs. 8, 9)

Blade thin, in oral view, straight to slightly curved throughout its length. Outline of oral edge, in direct lateral view, rising regularly from posterior end in a low convexity for three fourths the length; convexity nearly parallels aboral outline; anterior one third distinct from remainder of blade and consists of 4 or 5 slightly larger, erect equal denticles. Oral denticles about 14, laterally compressed, sharp, fused throughout most of their length yet separated one from the other by a slight groove; denticles blunt at posterior end and become progressively inclined backward. Individual nature of denticles can be seen in transmitted light extending to near aboral edge. Two or three suppressed germ denticles occur at anterior end of navel. Aboral edge sharp; in lateral view, anterior one third straight to slightly offset upward to meet anterior edge; arched at midlength with marked down sweep of posterior end; navel shallow, centering at about midlength of blade, pointed posteriorly, extending as a small groove anteriorly and posteriorly to near ends of blade; lips thin, moderately expanded.

This species has much in common with *S. crassidentatus* (Branson), but the latter is less arched in posterior part and the former has 4 or 5 sub-terminal denticles at anterior end rather than 2.

This species differs from *S. parvus* (Huddle) in that the denticles are not rounded, and are free throughout a greater part of their length.

OCCURRENCE: Prospect Hill siltstone, loc. 2.

PARATYPES: University of Missouri, C.820-2.

Spathognathodus sp. A.

(Pl. 2, fig. 33)

Bar deep; blade-like near posterior end; arched slightly; straight except for inward flexure of posterior end. Denticles irregular in size and shape; slightly compressed; fused to near their apices;

larger on anterior limb and grading to small near posterior end. Aboral surface moderately sharp apical pit in front of mid-length, elongate, with antero-posterior extensions; edges thickened, but not flaring.

OCCURRENCE: English River siltstone, loc. 4.

FIGURED SPECIMEN: University of Missouri, C.821-2.

Spathognathodus sp. B.

(Pl. 2, fig. 31)

Blade of medium thickness; sinuous, but regularly curved throughout its length; oral outline viewed laterally, rising evenly from anterior edge; anterior margin evenly curved to anterior edge of navel. Aboral edge nearly straight; navel of medium size, shallow, asymmetrical, rounded at front, narrowing to a point at back, centering at midlength; lateral lips thick, small, moderately flaring. Germ denticles evident in transmitted light throughout length of blade, more numerous than oral terminations in posterior three quarters. Oral denticles about 15, coalesced to near their apices.

OCCURRENCE: English River siltstone, loc. 4.

FIGURED SPECIMEN: University of Missouri, C.821-1.

Genus *Subbryantodus* Branson and Mehl

Subbryantodus minutus Thomas, n. sp.

(Pl. 3, fig. 28)

Blade-like, highly arched, with sharp flexure at apex, blades forming about a right angle; anterior blade deeper than posterior; posterior blade twisted so that oral side is directed outward. Denticles of anterior blade 4, laterally compressed, short with sharp free apices, inclined posteriorly. Apical denticle only slightly larger than others, otherwise similar. Denticles of posterior blade 9, shorter than on anterior blade, otherwise similar. Apical pit subcircular, small, extends along blades as faint groove to near extremities.

OCCURRENCE: English River siltstone, loc. 2.

HOLOTYPE: University of Missouri, C.821-4.

Genus *Prioniodella* Ulrich and Bassler

Prioniodella ? sp.

(Pl. 2, fig. 17)

Barlike in direct oral view, straight through mid-length, anterior end flexed inward; posterior end flexed and twisted outward. Denticles laterally compressed, irregular in size, evident as germ denticles to near base of unit, with no suppression of germ denticles evident. Aboral edge sharp; apical pit a short slit along thin edge.

OCCURRENCE: Maple Mill shale, loc. 14.

FIGURED SPECIMEN: University of Missouri, C.825-5.

REFERENCES CITED

Bain, H. F. (1895a) *The geology of Washington County*, Iowa Geol. Survey, Ann. Rept., vol. 5, p. 117–173.

——— (1895b) *Central Iowa section of the Mississippian series*, Am. Geol., vol. 15, p. 317–325.

Branson, E. B. (1914) *The Devonian fishes of Missouri*, Univ. Mo., Bull., vol. 15, p. 69–72, 4 pls.

——— (1922) *The Devonian of Missouri*, Mo. Bur. Geol. Mines, vol. 17, p. 1–275, 72 pls., 10 figs.

——— (1938) *Stratigraphy and paleontology of the Lower Mississippian of Missouri*, Univ. Mo. Stud., vol. 13, no. 4, pt. 2, p. 1–234, 27 pls., 8 figs.

——— (1940) *Devonian of Northeastern Missouri*, Ill. Geol. Survey, Dedication Mineral Conf., no. 68, p. 174–181.

——— (1944) *Geology of Missouri*, Univ. Mo. Stud., vol. 19, no. 3, p. 11–495, 49 pls.

Branson, E. B., and Mehl, M. G. (1933) *Conodont Studies nos. 1–3*, Univ. Mo. Stud., p. 1–300, 24 pls., 11 charts.

——— — ——— (1938) *The conodont genus* Icriodus *and its stratigraphic distribution*, Jour. Paleont., vol. 12, p. 97–106, 1 pl.

——— — ——— (1940) *The recognition and interpretation of mixed conodont faunas*, Denison Univ., Sci. Lab. Bull., vol. 35, p. 195–209.

——— — ——— (1941) *New and little known Carboniferous conodont genera*, Jour. Paleont., vol. 15, p. 97–106, 1 pl.

——— — ——— (1944) *Conodonts*, In *Index fossils of North America*, John Wiley and Sons, New York, p. 235–246, 2 pls.

——— — ——— (1948) *Conodont homonyms and names to replace them*, Jour. Paleont., vol. 22, p. 527.

Branson, E. R. (1933) *Conodonts from the Hannibal formation of Missouri*, Univ. Mo. Stud., vol. 8, no. 4, p. 301–343, 4 pls.

Cooper, C. L. (1939) *Conodonts from a Bushberg-Hannibal horizon in Oklahoma*, Jour. Paleont., vol. 13, p. 379–422, 9 pls.

——— and Sloss, L. L. (1943) *Conodont fauna and distribution of a lower Mississippian black shale in Montana and Alberta*, Jour. Paleont., vol. 17, p. 168–176, 2 pls.

Cooper, G. A. et al (1942) *Correlation of the Devonian sedimentary formations of North America*, Geol. Soc. Am., Bull., vol. 53, p. 1729–1794, 1 pl., 1 fig.

Easton, W. H. (1944) *Corals from the Chouteau and related formations of the Mississippi Valley region*, Ill. Geol. Survey, Rept. Invest., no. 97, p. 1–93, 16 pls.

Ellison, S. (1946) *Conodonts as Paleozoic guide fossils*, Am. Assoc. Petrol. Geol., Bull., vol. 30, p. 93–110, 3 figs.

Grohskopf, J. G., Hinchey, N. S., and Greene, F. C. (1939) *Subsurface geology of northeastern Missouri*, Mo. Geol. Surv. and water res., 60th bienn. rept., p. 5–160, 3 pls.

Hass, W. H. (1934) *Corrections to the Kinderhook conodont fauna, Little Rocky Mountains, Montana*, Jour. Paleont., vol. 17, p. 307–309.

——— (1947) *Conodont zones in upper Devonian and lower Mississippian formations of Ohio*, Jour. Paleont., vol. 21, p. 131–141, 6 tables.

Hinde, C. J. (1879) *Conodonts from Chazy and Cincinnati group, and from the Hamilton and Genesee shale in Canada and the United States*, Quart. Jour., Geol. Soc. London, p. 351–369.

Holmes, G. B. (1928) *A bibliography of the conodonts with descriptions of early Mississippian species*, U. S. Nat. Mus., Pr., vol. 72, p. 1–38, 11 pls.

Huddle, J. W. (1934) *Conodonts from the New Albany shale of Indiana*, Bull. Am. Paleont., vol. 21, no. 72, 12 pls.

Keyes, C. R. (1892a) *The principal Mississippian section*, Geol. Soc. Am., Bull., vol. 3, p. 283–300.

——— (1892b) *Geologic formations of Iowa*, Iowa Geol. Survey, Ann. Rept., vol. 1, p. 1–467, 10 pls.

——— (1895) *Economic geology of Des Moines County*, Iowa Geol. Survey, vol. 3, p. 413–492.

Knechtel, M. M., and Hass, W. H. (1938) *Kinderhook conodonts from Little Rocky Mountains, northern Montana*, Jour. Paleont., vol. 12, p. 518–520.

Laudon, L. R. (1929) *The stratigraphy of the Kinderhook series of Iowa*, Iowa Geol. Survey, Ann. Rept., vol. 35, p. 339–451.

Meek, F. B., and Worthen, A. H. (1861) *Age of the Goniatite limestone at Rockford, Indiana*, Am. Jour. Sci., 2d ser. vol. 32, p. 167–177; p. 288.

Miller, A. K., and Youngquist, W. (1947) *Conodonts from the type section of the Sweetland Creek shale in Iowa*, Jour. Paleont., vol. 21, no. 6, p. 501–517, 4 pls.

——— (1948) *Additional conodonts from the Sweetland Creek shale of Iowa*, Jour. Paleont., vol. 22, p. 440–450, 2 pls.

Moore, R. C. (1928) *Early Mississippian formations in Missouri*, Mo. Bur. Geol. Mines, vol. 21, 2d ser., p. 7–278.

Pander, C. H. (1856) *Monographie der fossilen Fische des silurischen Systems der russisch-baltischen Gouvernements*, Kaiser. Akad. Wiss., p. 1–96, pls. 1–9.

Stauffer, C. R. (1938) *Conodonts from the Olentangy shale*, Jour. Paleont., vol. 12, p. 411–443, 6 pls.

Taylor, L. (1942) *Conodonts and age of the Welden limestone*, Univ. Mo., unpublished Master's thesis.

Udden, J. A. (1900) *Geology of Louisa County*, Iowa Geol. Survey, Ann. Rept., vol. 11, p. 57–126.

Ulrich, E. O., and Bassler, R. S. (1926) *A classification of the tooth-like fossils, conodonts, with descriptions of American Devonian and Mississippian species*, U. S. Nat. Mus. Pr., vol. 68, p. 1–63, 11 pls.

Van Tuyl, F. M. (1921) *The stratigraphy of the Mississippian formations of Iowa*, Iowa Geol. Survey, Ann. Rept., vol. 30, p. 39–374, 6 pls., 16 figs.

Weller, J. M., and Sutton, A. H. (1940) *Mississippian border of eastern interior basin*, Am. Assoc. Petrol. Geol., Bull., vol. 24, no. 5, p. 765–858.

——— *et al.* (1948) *Correlation of the Mississippian formations of North America*, Geol. Soc. Am., Bull., vol. 59, p. 91–196, 2 pls., 7 figs.

Weller, S. (1899) *The succession of fossil faunas in the Kinderhook beds at Burlington, Iowa*, Iowa Geol. Survey, Ann. Rept., vol. 10, p. 43–79.

——— (1900) *Kinderhook faunal studies no. 2, The fauna of the Chonopectus sandstone at Burlington*, Iowa, St. Louis Acad. Sci., Tr., vol. 10.

——— (1901) *Kinderhook faunal studies no. 3, The faunas of beds no. 3 to no. 7 at Burlington, Iowa*, St. Louis Acad. Sci., Tr., vol. 11, p. 147–214.

——— (1905) *The northern and southern Kinderhook faunas*, Jour. Geol., vol. 13, p. 617–634.

——— (1909) *Correlation of the middle and upper Devonian and the Mississippian faunas of North America*, Jour. Geol., vol. 17, p. 257–285.

Williams, J. S. (1943) *Stratigraphy and fauna of the Louisiana limestone of Missouri*, U. S. Geol. Survey, Prof. Paper 203, p. 1–129, 9 pls., 9 figs.

Worthen, A. H. (1866) *Geology of Illinois*, Ill. Geol. Survey, vol. 1, Section on Kinderhook Group, p. 108–118.

Youngquist, W., and Peterson, R. F. (1947) *Conodonts from the Sheffield formation of north-central Iowa*, Jour. Paleont., vol. 21, p. 242–253, 3 pls.

DEPARTMENT OF GEOLOGY, IOWA STATE COLLEGE, AMES, IOWA

MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, FEBRUARY 18, 1948

EXPLANATION OF PLATES

PLATE 1.—CONODONTS FROM THE MAPLE MILL SHALE

Figures enlarged approximately 25 diameters unless otherwise stated.

Figure

(1, 7)—***Prioniodus obtusus*** Branson and Mehl; (1) Inner lateral view of a small specimen, Univ. Mo., C.826-1; (7) Inner lateral view, Univ. Mo., C.832-1, loc. 9.

(2)—***Hindeodella*** sp.; Inner lateral view of a broken specimen, Univ. Mo., C.833-2.

(3)—***Hindeodella*** cf. *H. gladiola* E. R. Branson; Inner lateral view, Univ. Mo., C.824-2, loc. 13.

(4)—***Hindeodella*** cf. *H. corpulenta* Branson and Mehl; Inner lateral view, Univ. Mo., C.826-5, loc. 11.

(5)—***Hindeodella***? sp.; Inner lateral view of the posterior end of a broken specimen, Univ. Mo., C.825-3, loc. 13.

(6)—***Lonchodina*** sp. B.; Inner lateral view, Univ. Mo., C.823-5, loc. 13, p. 427.

(8)—***Euprioniodina iowaensis*** Thomas, n. sp.; Inner lateral view of the holotype, Univ. Mo., C.830-4, loc. 14, p. 420.

(9)—***Euprioniodina lateralis*** Thomas, n. sp.; Inner lateral view of the holotype, Univ. Mo., C.829-3, loc. 14, p. 420.

(10, 13, 26)—***Palmatolepis perlobata*** Ulrich and Bassler; (10) Oral view, Univ. Mo., C.822-3, (13) Enlarged 17 diameters, Univ. Mo., C.822-2, (26) Oral view, Univ. Mo., C.822-3, loc. 14.

(11)—***Ancyrognathus irregularis*** Branson and Mehl; Oral view, Univ. Mo., C.834-1, loc. 14.

(12)—***Hindeodella***? sp.; Inner lateral view, Univ. Mo., C.833-2, loc. 13, p. 423.

(14)—***Nothognathella gigantea*** Thomas, n. sp.; Enlarged 17 diameters, Inner lateral view of the holotype, Univ. Mo. C.833-5, loc. 13, p. 427.

(15)—***Nothognathella minuta*** Thomas, n. sp.; Inner lateral view of the holotype; Univ. Mo., C.827-1, loc. 13, p. 427.

(16)—***Hibbardella longipostica*** Thomas, n. sp.; Oral view of the holotype, Univ. Mo., C.825-1, loc. 13, p. 421.

(17, 18)—***Icriodus*** cf. *I. rectus* Youngquist and Peterson; Oral and aboral views of 2 specimens, Univ. Mo., C.831-1, loc. 9.

(19)—***Palmatolepis glabra*** Ulrich and Bassler; Oral view, Univ. Mo., C. 822-4, loc. 14.

(20)—***Ancyrognathus minuta*** Thomas, n. sp.; Oral view of the holotype, Univ. Mo., C.833-1, loc. 13, p. 416.

(21)—***Diplododella*** sp. A.; Lateral posterior view of an incomplete specimen, Univ. Mo., C.830-3, loc. 13, p. 420.

(22)—***Diplododella alternata*** (Branson and Mehl); Posterior view of a broken specimen, Univ. Mo., C.828-1, loc. 13.

(23)—***Polygnathus semicostata*** Branson and Mehl; Oral view, Univ. Mo., C.828-4, loc. 13.

(24)—***Polygnathus sandushiensis*** Stauffer; Enlarged 17 diameters, Oral view, Univ. Mo., C.823-4, loc. 13.

(25)—***Icriodus constrictus*** Thomas, n. sp.; Oral view of the holotype, Univ. Mo., C.831-2, loc. 13, p. 416.

(27)—***Lonchodina*** cf. *L. prava* Huddle; Lateral view of an incomplete specimen, Univ. Mo., C.826-3, loc. 2.

(28)—***Prioniodus molestus*** Branson and Mehl; Inner lateral view, Univ. Mo., C.803-3, loc. 9.

(29)—***Trichonodella robusta*** (Branson and Mehl); Posterior view of an incomplete specimen, Univ. Mo., C. 812-1, loc. 13.

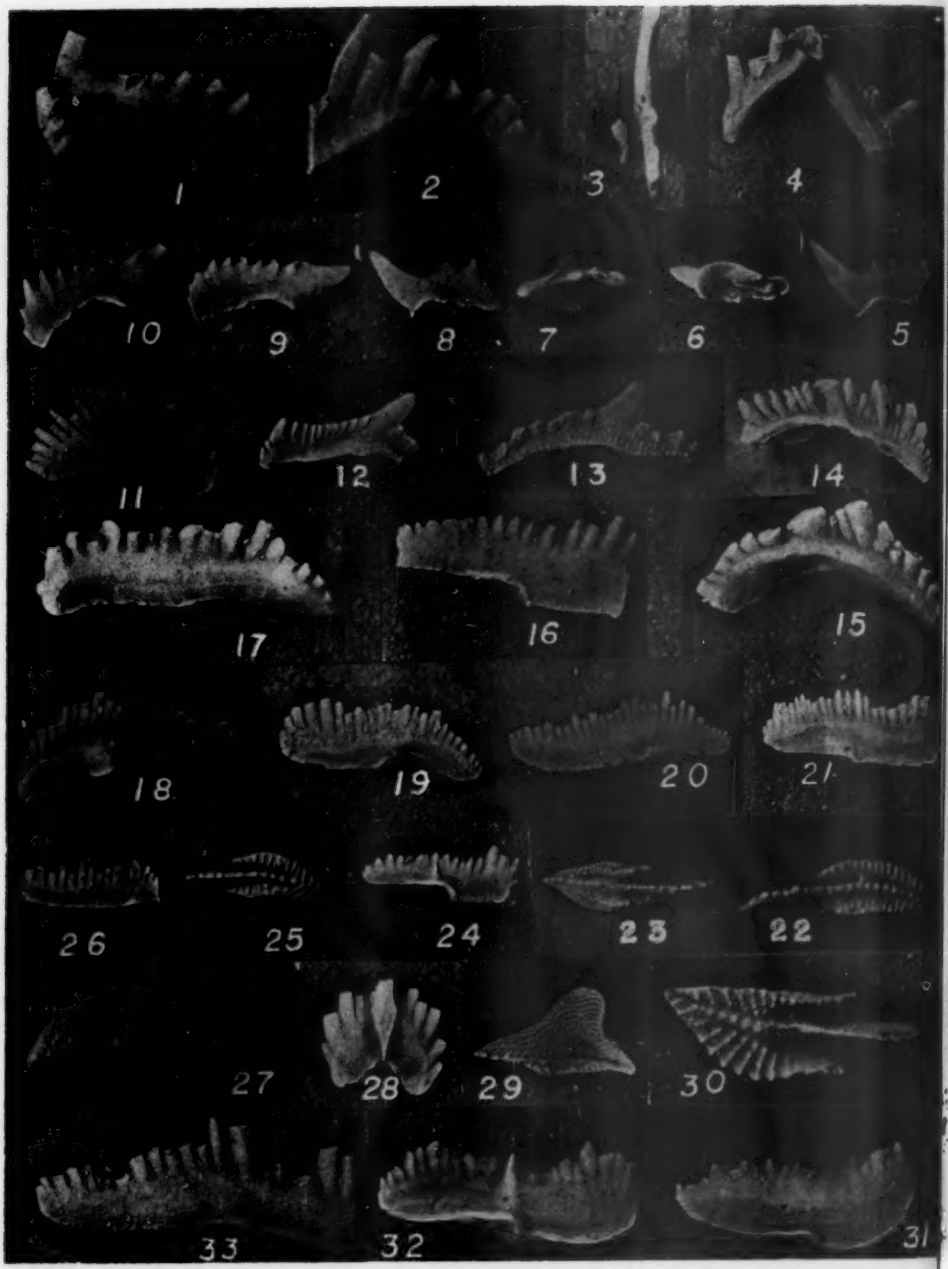
(30)—***Ligonodina robusta*** Branson and Mehl; Inner lateral view, Univ. Mo., C.812-1, loc. 5.

(31)—***Polylophodonta acuta***? Thomas, n. sp.; Oral view of the holotype, Univ. Mo., C.825-2, loc. 13, p. 419.

(32)—***Polygnathus*** ? ***millensis*** Thomas, n. sp.; Oral view of the holotype, Univ. Mo., C.826-2, loc. 13, p. 417.

(33, 34)—***Polygnathus granulosa*** Branson and Mehl; (33) Oral view, Univ. Mo., C.824-3, loc. 13; (34) Oral view, showing variation within this species, Univ. Mo., C.824-3, loc. 13.

CONODONTS FROM THE MAPLE MILL SHALE



CONODONTS FROM THE MAPLE MILL SHALE

PLATE 2.—CONODONTS FROM THE MAPLE MILL SHALE

Specimens here figured are from the Maple Mill shale except figures 31, 32, and 33. Figures enlarged approximately 25 diameters unless otherwise stated.

Figure

(1)—*Ligonodina* sp. A.; Inner lateral view, Univ. Mo., C.830-1, loc. 13, p. 424.
(2)—*Bryantodus* sp. A.; Inner lateral view of an incomplete specimen, Univ. Mo., C.822-1, loc. 13, p. 426.
(3)—*Hibbardella recursata* Thomas, n. sp.; Posterior view of the holotype, Univ. Mo., C.824-4, loc. 13, p. 422.
(4)—*Lonchodina* sp. A.; Inner lateral view of a broken specimen, Univ. Mo., C.829-4, loc. 2, p. 426.
(5)—*Pelekysgnathus nodosa* Thomas, n. sp.; Lateral view of the holotype, Univ. Mo., C.831-5, loc. 14, p. 425.
(6, 7, 8)—*Pelekysgnathus communis* Thomas, n. sp.; (6) Aboral view of a syntype; (7) Oral view of a syntype; (8) Lateral view of a syntype, Univ. Mo., C. 831-3, loc. 14, p. 424.
(9)—*Pelekysgnathus costata* Thomas, n. sp.; Inner lateral view of the holotype, Univ. Mo., C.831-4 loc. 2, p. 424.
(10)—*Pelekysgnathus inclinata* Thomas n. sp.; Inner lateral view of the genotype, Univ. Mo., C.834-4, loc. 14, p. 424.
(11)—*Ozarkodina* cf. *O. regularis* Branson and Mehl; Inner lateral view of a specimen from the Maple Mill, Univ. Mo. C.829-1, loc. 13, p. 428.
(12)—*Bryantodus lateralus* Thomas, n. sp.; Inner lateral view of the holotype, Univ. Mo., C.832-3, loc. 13, p. 425.
(13)—*Bryantodus millensi* Thomas, n. sp.; Inner lateral view of the holotype, Univ. Mo., C.827-2, loc. 13, p. 425.
(14)—*Bryantodus* sp?; Inner lateral view of a specimen from the Maple Mill, Univ. Mo., C.826-4, loc. 14, p. 426.
(15)—*Bryantodus* sp.; Inner lateral view of a Maple Mill specimen, Univ. Mo., C.830-2, loc. 13, p. 426.
(16, 24) —*Spathognathodus crassidentatus* (Branson and Mehl); (16) Inner lateral view, Univ. Mo., C.825-4; (24) Inner lateral view of a small specimen that has a ridge on the side, Univ. Mo., C.824-5, loc. 13.
(17)—*Prioniodella* ? sp.; Inner lateral view, Univ. Mo., C.825-5, loc. 14, p. 430.
(18)—*Ozarkodina millensis* Thomas, n. sp.; Outer lateral view of the holotype, Univ. Mo., C.829-5, loc. 13, p. 428.
(19, 21) —*Spathognathodus strigosus* (Branson and Mehl); (19) Inner lateral view, Univ. Mo., C.828-3, loc. 13; (21) Outer lateral view, Univ. Mo., C.825-4, loc. 14.
(20)—*Spathognathodus flexus* Thomas, n. sp.; Inner lateral view of the holotype, Univ. Mo., C.834-5, loc. 14. p.429.
(22, 25)—*Polygnathus* sp. A.; Oral views of two variable specimens, Univ. Mo., C.827-4, loc. 14, p. 419.
(23)—*Polygnathus perplexa* ? Thomas, n. sp.; Enlarged 17 diameters, Oral view of holotype, Univ. Mo., C.827-3, loc. 14, p. 418.
(26)—*Spathognathodus inornatus* (Branson and Mehl); Inner lateral view of a broken specimen, Univ. Mo., C.807-3, loc. 14.
(27)—*Palmatolepis* ? *irregularis* Thomas, n. sp.; Oral view of the holotype, Univ. Mo., C.830-5, loc. 14, p. 416
(28)—*Hibbardella plana* Thomas, n. sp.; Posterior view of the holotype, Univ. Mo., C.827-5, loc. 13, p. 422.
(29)—Specimen A. Enlarged 17 diameters, Oral view of a distinctive complete specimen that cannot be referred to any genus, Univ. Mo., C.828-2, loc. 14.
(30)—*Polygnathus triangularis* Branson and Mehl; Oral view, Univ. Mo., C.808-2, loc. 2.
(31)—*Spathognathodus* sp. B.; Inner lateral view of a specimen from the English River, Univ. Mo., C.821-1, loc. 4, p. 430.
(32)—*Spathognathodus irregularis* (E. R. Branson); Inner lateral view of a specimen from the English River, Univ. Mo., C.804-5, loc. 12.
(33)—*Spathognathodus* sp. A.; Inner lateral view of a specimen from the English River, Univ. Mo., C.821-2, loc. 4, p. 429.

PLATE 3.—ENGLISH RIVER AND PROSPECT HILL CONODONTS

Figures enlarged approximately 25 diameters unless otherwise stated.

Figure

(1)—*Siphonodella sexplicata* (Branson and Mehl); Oral view of a specimen from the Prospect Hill, Univ. Mo., C.819-5, loc. 1.

(2, 3, 6)—*Siphonodella quadruplicata* (Branson and Mehl), (2) Oral view of a specimen from the Prospect Hill, loc. 2, Univ. Mo., C.809-1; (3) Oral view of a specimen from the English River, Univ. Mo., C.805-1, loc. 12; (6) Oral view of a specimen from the English River, Univ. Mo., C.814-3, loc. 11.

(4)—*Palmatodella* sp. indet.; Inner lateral view of an incomplete specimen from the English River, Univ. Mo., C.814-2, loc. 12, p. 428.

(5)—*Polygnathus orthoconstricta* Thomas, n. sp.; Oral view of the holotype from the Prospect Hill, Univ. Mo., C.819-4, loc. 2, p. 418.

(7)—*Polygnathus corrugata* E. R. Branson; Enlarged 17 diameters, Oral view of a specimen from the Prospect Hill, Univ. Mo., C.819-2, loc. 2.

(8, 9)—*Siphonodella duplicata* (Branson and Mehl); (8) Oral view of a specimen from the English River, Univ. Mo., C.809-5, loc. 11, (9) Oral view of a specimen from the Prospect Hill, Univ. Mo., C.819-3, loc. 2.

(10, 12)—*Polygnathus anica* Cooper; Oral view of two specimens from the English River, Univ. Mo., C.804-3, loc. 13.

(11)—*Polygnathus lobata* Branson and Mehl; Oral view of a specimen from the English River, Univ. Mo., C.808-1, loc. 12.

(13)—*Ozarkodina* sp. A.; Lateral view of a specimen from the Prospect Hill, Univ. Mo., C.817-2, loc. 2, p. 428.

(14)—*Ligonodina flexuosa* Branson and Mehl; Inner lateral view of a small specimen from the Prospect Hill, Univ. Mo., C.818-5, loc. 2.

(15)—*Diplododella symmetrica* ? Huddle; Posterior view of a broken specimen from the English River, Univ. Mo., C.803-5, loc. 11.

(16)—*Bryantodus scolops* Cooper; Inner lateral view of a specimen from the English River, Univ. Mo., C.815-1, loc. 10.

(17)—*Pinacognathus* cf. *P. profundus* (Branson and Mehl) Inner lateral view of a specimen from the Prospect Hill, Univ. Mo., C.811-3, loc. 2.

(18, 20)—*Solenodella tenera* (E. R. Branson); Inner lateral view of 2 specimens from the English River, Univ. Mo., C.812-2, loc. 14.

(19)—*Solenodella lateranodosa* Thomas, n. sp.; Inner lateral view of the holotype from the English River, Univ. Mo., C.813-1, loc. 12, p. 428.

(21)—*Bryantodus planus* ? Branson and Mehl; Inner lateral view of a specimen from the Prospect Hill, Univ. Mo., C.811-5, loc. 2, p. 425.

(22)—*Polygnathus scapha* Cooper; Oral view of a specimen from the English River, Univ. Mo., C.808-3, loc. 9.

(23)—*Euprioniodina* sp. A.; Inner lateral view of an incomplete specimen from the English River, Univ. Mo., C.806-5, loc. 12, p. 421.

(24)—*Gnathodus* sp. indet.; Oral view of a small specimen from the English River, Univ. Mo., C.812-4, loc. 5, p. 416.

(25)—*Pseudopolygnathus brevimarginata* E. R. Branson; Oral view of a small specimen from the Prospect Hill, Univ. Mo., C.814-5, loc. 2.

(26)—*Solendodella* cf. *S. bialata* (Branson and Mehl); Oral view of a specimen from the English River, Univ. Mo., C.813-4, loc. 12, p. 429.

(27)—*Ligonodina minuta* Thomas, n. sp.; Inner lateral view of the holotype from the English River, Univ. Mo., C.815-5, loc. 12, p. 423.

(28)—*Subbryantodus minutus* Thomas, n. sp.; Inner lateral view of the holotype from the English River, Univ. Mo., C.821-4, loc. 2, p. 430.

(29)—*Diplododella* ? sp.; Oral view of an incomplete bar from the English River, Univ. Mo., C.815-4, loc. 4, p. 420.

(30)—*Hindeodella* sp.?; Oral view of an incomplete bar from the English River, Univ. Mo., C.816-5, loc. 1.

(31)—*Hindeodella acuta* Branson and Mehl; Inner lateral view of a specimen from the Prospect Hill, Univ. Mo., C.809-3, loc. 2, p. 422.

(32)—*Hindeodella curvata* Branson and Mehl; Lateral view of a broken specimen from the English River, Univ. Mo., C.803-1, loc. 11.

(33)—*Polygnathus* sp. B.; Oral view of a small specimen from the Prospect Hill, Univ. Mo., C.818-3, loc. 14, p. 419.

(34)—*Polygnathus* sp. C.; Oral view of a small specimen from the English River, Univ. Mo., C.813-3, loc. 12, p. 419.

(35)—*Polygnathus perplana* E. R. Branson; Oral view of a specimen from lower English River, Univ. Mo., C.807-2, loc. 5.

(36)—*Polgnathus inornata* E. R. Branson; Enlarged 17 diameters; Oral view of a specimen from the Prospect Hill, Univ. Mo., C.811-1, loc. 1.

(37)—*Polygnathus communis* Branson and Mehl; Oral view of a specimen from the Prospect Hill, Univ. Mo., C.803-2, loc. 2.

(38)—*Polygnathus longipostica* Branson and Mehl; Enlarged 17 diameters, Oral view of a specimen from the Prospect Hill, Univ. Mo., C.820-3, loc. 2.

(39)—*Polygnathus permarginata* E. R. Branson; Oral view of a specimen from the Englihs River, Univ. Mo., C.816-3, loc. 12.

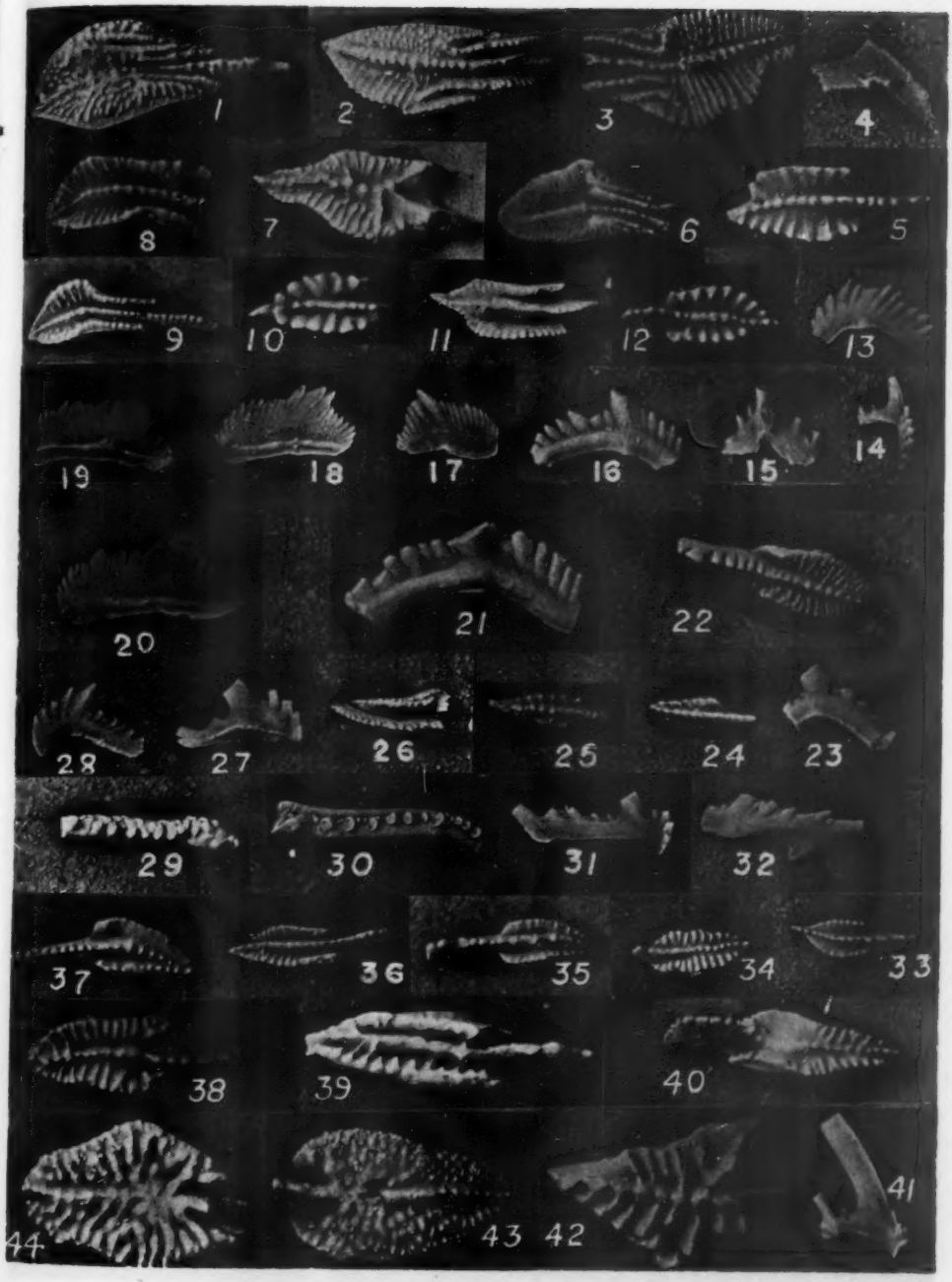
(40)—*Polygn athus gigantea* Thomas, n. sp.; Enlarged 17 diameters, Oral view of the holotype from the Prospect Hill, Univ. Mo., C.819-1, loc. 2, p. 417.

(41)—*Ligonodina delicata* ? Branson and Mehl, Inner lateral view of a specimen from the English River, Univ. Mo., C.805-2, loc. 14.

(42)—*Pseudopolygnathus* cf. *P. asymmetrica* E. R. Branson; Oral view of a specimen from the Prospect Hill, Univ. Mo., C.811-4, loc. 1.

(43)—*Polygnathus nodosa* Thomas, n. sp.; Oral view of the holotype from the English River, Univ. Mo., C.806-2, loc. 5, p. 418.

(44)—*Polygnathus concava* Thomas, n. sp.; Oral view of the holotype from the English River, Univ. Mo., C.821-3, loc. 2, p. 417.



ENGLISH RIVER AND PROSPECT HILL CONODONTS

ENGLISH RIVER AND PROSPECT HILL CONODONTS

PLATE 4.—ENGLISH RIVER AND PROSPECT HILL CONODONTS

All figures enlarged approximately 25 diameters unless otherwise stated.

Figure

(1)—*Hindeodella* sp. A.; Inner lateral view of one specimen from the Prospect Hill, Univ. Mo., C.809-4, loc. 2, p. 423.

(2)—*Hindeodella* sp. indet.; Inner lateral view of one specimen from the Prospect Hill, Univ. Mo., C.818-4, loc. 2, p. 422.

(3)—*Centrognathodus dubius* Thomas, n. sp.; Inner lateral view of holotype from the Prospect Hill, Univ. Mo., C.817-4, loc. 2, p. 419.

(4, 5)—*Spathognathodus inornatus* (Branson and Mehl); (4) Outer lateral view of a specimen from the lower English River, Univ. Mo., C.806-1, loc. 8; (5) Inner lateral view of a specimen from the lower English River, Univ. Mo., C.807-3, loc. 8.

(6)—*Spathognathodus crassidentatus* (Branson and Mehl); Inner lateral view of a specimen from the English River, Univ. Mo., C.818-1, loc. 13.

(7)—*Spathognathodus aciedentatus* (E. R. Branson); Inner lateral view of a specimen from the English River, Univ. Mo., C.808-5, loc. 12.

(8, 9)—*Spathognathodus quintidentatus* Thomas, n. sp.; (8) Inner lateral view of a syntype; (9) Oral view of a syntype; Prospect Hill, Univ. Mo., C.820-2, loc. 2, p. 429.

(10)—*Spathognathodus costatus* (E. R. Branson); Enlarged 17 diameters; Oral view of a specimen from the English River, Univ. Mo., C.804-2, loc. 9.

(11)—*Spathognathodus tridentatus* (E. R. Branson); Oral view of an incomplete specimen from the English River, Univ. Mo., C.815-3, loc. 5.

(12)—*Hindeodella curvata* Branson and Mehl; Outer lateral view of a broken specimen from the English River, Univ. Mo., C.803-1, loc. 11.

(13)—*Spathognathodus delicatulus* (E. R. Branson); Inner lateral view of a small specimen from the English River, Univ. Mo., C.806-4, loc. 8.

(14)—*Lonchodina* sp. C.; Inner lateral view of an incomplete specimen from the Prospect Hill, Univ. Mo., C.820-1, loc. 2, p. 427.

(15)—*Spathognathodus strigosus* (Branson and Mehl); Inner lateral view of a specimen from the Prospect Hill, Univ. Mo., C.817-3, loc. 11.

(16)—*Pseudopolygnathus constricticterminata* Thomas, n. sp.; Oral view of a specimen from the English River, Univ. Mo., C.807-4, loc. 12, p. 428.

(17)—*Pseudopolygnathus prima* Branson and Mehl; Outer view of a specimen from the Prospect Hill, Univ. Mo., C.817-5, loc. 2.

(18)—*Pseudopolygnathus* cf. *P. crenulata* E. R. Branson; Oral view of a specimen from the Prospect Hill, Univ. Mo., C.810-3, loc. 2.

(19)—*Bryantodus giganteus* E. R. Branson; Enlarged 17 diameters, Inner lateral view of a specimen from the Prospect Hill, Univ. Mo., C.811-2, loc. 2.

(20, 34)—*Prioniodus aphanes* (Cooper); (20) Inner lateral view; from the English River; (34) Inner lateral view; from the Prospect Hill, Univ. Mo., C.817-1, loc. 11.

(21)—*Euprioniodina aphanes* Cooper; Inner lateral view of a small specimen from the Prospect Hill, Univ. Mo., C.810-5, loc. 12.

(22)—*Ligonodina delicata* Branson and Mehl; Inner lateral view; from the English River, Univ. Mo., C.805-4, loc. 8.

(23, 24)—*Ligonodina dubia* Thomas, n. sp.; (23) Outer lateral view of a syntype; (24) Inner lateral view of a syntype; Prospect Hill, Univ. Mo., C.810-2, loc. 2, p. 423.

(25)—*Hibbardella macrodentata* Thomas, n. sp.; Posterior view of the holotype from the English River, Univ. Mo., C.820-5, loc. 12, p. 422.

(26)—*Prioniodus barbatus* Branson and Mehl; Inner lateral view; from the English River, Univ. Mo., C.816-2, loc. 12.

(27)—*Prioniodus corniger* E. R. Branson; Inner lateral view; from the Prospect Hill, Univ. Mo., C.805-3, loc. 2.

(28)—*Ozarkodina* cf. *O. elongata* Branson and Mehl; Inner lateral view of an English River specimen, Univ. Mo., C.813-5, loc. 10, p. 428.

(29)—*Bryantodus flexus*? Branson and Mehl; Inner lateral view of an incomplete specimen from the English River, Univ. Mo., C.808-4, loc. 12.

(30)—*Bryantodus* sp. B.; Inner lateral view of an incomplete specimen from the English River, Univ. Mo., C.820-4, loc. 11, p. 426.

(31)—*Hibbardella* sp. A.; Lateral view of an incomplete specimen from the Prospect Hill, Univ. Mo., C.818-2, loc. 11, p. 422.

(32)—*Trichonodella* sp.? Posterior view; English River, Univ. Mo., C.813-2, loc. 12, p. 425.

(33)—*Ligonodina gigantea* Thomas, n. sp.; Inner lateral view of the holotype from the Prospect Hill, Univ. Mo., C.810-1, loc. 2, p. 423.

(35)—*Prioniodus alatus*? Hinde; Inner lateral view of a specimen from the Prospect Hill, Univ. Mo., C.814-1, loc. 12.

(36)—*Bryantodus planus*? Branson and Mehl; Inner lateral view of an incomplete specimen from the English River, Univ. Mo., C.814-1, loc. 12.

(37)—*Euprioniodina symmetrica* Thomas, n. sp.; Inner lateral view of the holotype from the English River, Univ. Mo., C.815-2, loc. 11, p. 421.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 60, PP. 439–460, 3 FIGS., 1 PL. MARCH 1949

THE SYSTEM $MgO—SiO_2—H_2O$

BY N. L. BOWEN AND O. F. TUTTLE

CONTENTS

	Page
Abstract	440
Introduction	440
Experimental methods	440
Hydrothermal preparation of the pure mineral compounds	441
General statement	441
Forsterite	442
Enstatite	442
Talc	443
Sepiolite	443
Serpentine (chrysotile)	443
Anthophyllite	444
Brucite	444
Silica	444
Equilibria and the stability regions of the phases	446
General statement	446
Curve I	448
Curve II	448
Curve III	449
Curve IV	449
Curve V	449
Region above curve V	449
Composition of the vapor phase	449
Absence of a stability region for anthophyllite	450
Significance of the results	452
Experiments on the serpentinization of natural olivines	453
Origin of dunite, serpentine, and related intrusive rocks	454
Transformation of serpentine into higher-grade phases	457
Tectonic setting of serpentine and related intrusives	458
Limit of crustal existence of serpentine	459
Mutual relations of various rock types in ultramafic complexes	459
References cited	460

ILLUSTRATIONS

Figure	Page
1. Diagram showing composition (in moles) of the several phases in the system $MgO—SiO_2—H_2O$	442
2. Pressure-temperature curves (I–V) of univariant equilibrium in the system $MgO—SiO_2—H_2O$	447
3. Not impossible form of equilibrium diagram for temperatures immediately above Curve II of Figure 2	451

Plate	Facing page
1. Electron photomicrograph of crystals of synthetic serpentine	444

ABSTRACT

Equilibrium in the system MgO—SiO_2—H_2O has been determined at temperatures up to 1000°C and at maximum pressures of water vapor varying from 15,000 lbs/in² at this maximum temperature, to 30,000 lbs/in² in the range 900°—600°C, and 40,000 lbs/in² in the range 600°–300°C. Thus were fixed the univariant pressure-temperature curves of the following five reactions: I. serpentine + brucite ⇋ forsterite + vapor, II. serpentine ⇋ forsterite + talc + vapor, III. forsterite + talc ⇋ enstatite + vapor, IV. talc ⇋ enstatite + quartz + vapor, and V. brucite ⇋ periclase + vapor. Pure magnesian serpentine has a maximum temperature of existence at approximately 500°C, varying only about 10° in the whole range of pressure 2000 to 40,000 lbs/in². Forsterite is stable in contact with water vapor down to a temperature of about 430°C (at 15,000 lbs/in²). Only below that temperature is it transformed into serpentine and brucite. Iron-bearing olivines are stable in contact with water vapor down to still lower temperatures.

No liquid is formed in any composition of the system throughout the range of temperatures and pressures at which experiments were conducted, a condition which remains unchanged when the mixtures have upwards of 7 per cent FeO.

There is consequently no likelihood that any magma can exist that can be called a serpentine magma and certainly no possibility of its existence below 1000°C. There seems no escape from the conclusion that ultramafics can be intruded only in the solid state.

INTRODUCTION

Geologic field studies are usually concerned with end products of processes long since completed. Even the most detailed examination of these products may fail to yield unequivocal evidence of the nature of the processes. Rival hypotheses arise, and even after further observations the geologist is not infrequently left in a state of indecision as to their relative merits. Silicate rocks in particular pose many problems that appear to be incapable of solution by field methods alone, and it is but natural that an attempt be made to gain further light on these problems by laboratory studies of the behavior of silicates and silicate systems under controlled and measured conditions.

Few simple silicate systems embrace compositions that approach closely those of natural igneous and metamorphic rocks, but the binary system MgO—SiO_2 and the ternary system MgO—SiO_2—H_2O are significant exceptions to this rule. The substitution of only moderate amounts of iron oxides for a part of the magnesia gives a chemistry substantially that of certain peridoitites, pyroxenites, and serpentines—rocks of widespread occurrence and probably of unusual genetic significance. For this reason the laboratory investigation of these systems may be expected to yield results of notable value in problems of petrogeny. The study of the dry system was completed long since (Bowen and Andersen, 1914). We now present the results of a study of the system with water at pressures up to 40,000 lbs/in² and temperatures up to 1000°C.

EXPERIMENTAL METHODS

Investigation of equilibrium relations in various compositions of the system were carried out largely with the aid of apparatus designed by Tuttle (1948, p. 628). The

method permits the direct measurement of temperatures and pressures during a run and facilitates rapid cooling or quenching of the charge at its conclusion. For some purposes, and especially when a considerable quantity of product was desired, the type of autoclave designed at the Geophysical Laboratory for such purposes (Morey and Ingerson, 1937, p. 1121) was employed. Morey has modified it so that the pressure of water vapor can be pumped up and maintained at any desired and measured value, a distinct improvement over earlier procedure in which the pressure was merely calculated from the weight of water added and the internal volume of the bomb. Significant errors in values for the pressure may be introduced by this earlier procedure on account of imperfection in our knowledge of the properties of water at high temperatures.

The raw materials used were MgO (Baker's Analyzed) ignited to constant weight, precipitated SiO_2 or silica glass also ignited to constant weight, and distilled water. The dry oxides were mixed in the desired proportion and ground together to obtain as intimate a mixture as possible. They were then placed in platinum containers and heated in the pressure vessel at the desired temperature, under a measured pressure of water vapor. For some experiments, to be discussed in detail later, the initial material was serpentine, talc, brucite, forsterite, or enstatite which had been prepared in the Morey bomb, and in some instances the corresponding natural minerals were used.

It was found that convective circulation of water vapor took place in the pressure chamber and in the tube connecting it with the pump, even when the bore of this tube for a considerable distance from the pressure chamber was reduced to capillary size. As a result of this circulation SiO_2 was abstracted from the charge and deposited elsewhere in the apparatus, and a definite change of composition of the charge resulted, in spite of the fact that the solubility of SiO_2 in the vapor is excessively small. Moreover some iron oxide was at times similarly transferred to the charge from the steel parts of the apparatus. To reduce these effects the small platinum crucible was covered with another crucible inverted over it and telescoping with it in a very snug fit. Even with this arrangement transport of material to and from the charge was not entirely eliminated. A further step was therefore taken which solved the problem. The double crucible with its charge as just described was placed in another considerably larger crucible, and the space below the bottom, around the sides, and above the covered top of the interior double crucible was packed with a further quantity of the same preparation as the charge. The charge was thus surrounded by an envelope or buffer of its own material. The buffer effectively saturated the vapor, as it passed through it to the charge, with the same materials that it was capable of abstracting from the charge and abstracted any iron oxide present in the vapor.

HYDROTHERMAL PREPARATION OF THE PURE MINERAL COMPOUNDS

GENERAL STATEMENT

All the more familiar mineral compounds of magnesia and silica and of magnesia, silica, and water were readily prepared hydrothermally. Their identity was usually established by their optical properties, although, when the product was unusually

fine-grained, confirmation by the method of X-ray diffraction of the powder was necessary or at least desirable. Ordinarily a considerable quantity of product was desired, and the larger bomb was therefore commonly used. The phase compositions are plotted in Figure 1.

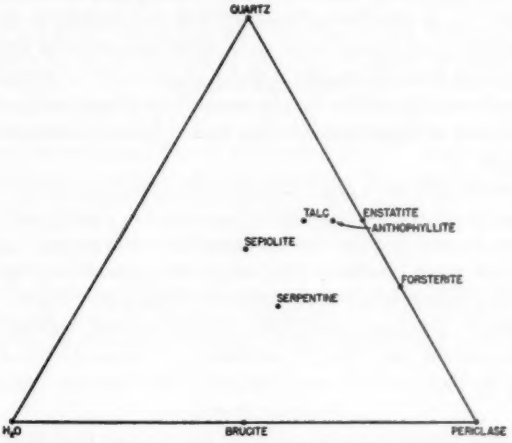


FIGURE 1.—*Diagram showing composition (in moles) of the several phases in the system, MgO-SiO_2-H_2O*

FORSTERITE

The compound Mg_2SiO_4 in the form, forsterite, is readily prepared hydrothermally by mixing the oxides in the proportions called for by the formula and heating them at a temperature of some 500°C or higher and at any pressure of water vapor from 2000 lbs/in² to 40,000 lbs/in². The ready growth of crystals of this very refractory anhydrous compound under hydrothermal conditions at rather low temperatures was unexpected, as was also the observation that of all the compounds of the system, not excepting the hydrous compounds, forsterite is easily the best crystallizer. Facetted crystals of dimensions greater than those shown by any other compound in the system were freely formed.

The optical properties are identical with those of crystals grown from dry melts at high temperatures.

The X-ray diffraction pattern of the powder is identical with that of synthetic forsterite made at high temperatures in the dry way and also with that of natural olivine close to Mg_2SiO_4.

ENSTATITE

The compound $MgSiO_3$ in the form, enstatite, is readily prepared by mixing the oxides in equivalent proportions and heating them together at temperatures of 700°C or higher, at pressures of water vapor of 5000 lbs/in² and upward. At lower temperatures other phases are formed, but a detailed discussion of stability fields is

reserved for a later page. Because a high temperature must be maintained, enstatite was prepared only in small quantities in the small bombs. It forms minute needle crystals which are usually large enough for measurement of the refractive indices in immersion media. Enstatite crystals were also grown under the same conditions using $MgSiO_3$ glass as the initial material.

The optical properties and the X-ray diffraction pattern are the same as those of natural enstatite.

TALC

The compound $Mg_3Si_4O_{10}(OH)_2$ (that is, $3MgO \cdot H_2O \cdot 4SiO_2$), having properties identical with those of the natural mineral, talc, can be prepared at all temperatures below about 800°C (details on a later page) by mixing MgO and SiO_2 in the formula proportions and subjecting them to pressures of water vapor from 6000 to 30,000 lbs/in^2. At temperatures around 350°C and lower and a pressure of water of 15,000 lbs/in^2 a product was obtained with the optical properties and X-ray diffraction pattern of sepiolite.

A number of chemical analyses of supposed talc in the literature have suggested to some investigators that talc can vary in composition, but present indications are that the materials examined were mixtures. In any case, in our synthetic preparations, if we use a slight excess of silica over that indicated by the accepted formula, some free SiO_2 is present with the talc and if we use a slight excess of MgO some forsterite appears with the talc at 525°C and 15,000 lbs/in^2. Our work, therefore, does not support the concept of variability in the composition of talc and shows that the ratio of MgO and SiO_2 is that of the accepted formula. The water content is also in accord with that formula, analysis of our product showing 4.6 per cent H_2O. The theoretical value is 4.75 per cent.

SEPIOLITE

The formation of sepiolite ($2MgO \cdot 3SiO_2 \cdot 2H_2O$?) has been mentioned. It has lower refraction and birefraction than talc and yields a somewhat different X-ray pattern. Our products always contained some talc. The full theoretical water content of sepiolite was never attained.

SERPENTINE (CHRYSOTILE)

The compound, $3MgO \cdot 2SiO_2 \cdot 2H_2O$, or $Mg_6Si_4O_{11}(OH)_6 \cdot H_2O$, with the properties of chrysotile, can be prepared at any temperature below 500° ± 10° and at pressures from 2000 to 40,000 lbs/in^2. Unlike all other phases in the system it never forms good crystals but always appears as minute fibers. It has the low refractive indices of chrysotile as distinct from the higher indices of antigorite. Examination by the method of differential thermal analysis[1] reveals a behavior characteristic of chrysotile. Photographed in the electron microscope the individual units are seen to be minute rods of characteristic shape (Pl. 1).[2]

[1] Carried out for us by Dr. George Faust of the U. S. Geological Survey to whom we express our thanks.

[2] Study under the electron microscope was kindly made for us at the National Bureau of Standards by Dr. M. Swerdlow through the courtesy of Dr. H. Insley.

An attempt was made to grow larger crystals of chrysotile by placing MgO and SiO_2 in separate crucibles in a bomb with water and permitting growth of the compound only by slow transfer of material from one crucible to the other through the vapor phase. No appreciable increase of size resulted.

The optical and X-ray properties of the synthetic chrysotile correspond with those of the natural mineral. The water content of the product of two different runs was 13.6 and 14.2 per cent as compared with a theoretical value of 13.0 per cent.

ANTHOPHYLLITE

Crystals having the properties of anthophyllite were prepared, together with a small amount of silica set free in the reaction, by heating synthetic talc for 1 hour at 800°C under a pressure of 15,000 lbs/in^2 of water vapor. The crystals are minute needles with parallel extinction, and the refractive index $\gamma = 1.61$ ca. The X-ray diffraction pattern corresponds with that of natural anthophyllite. No success was achieved in the attempt to make anthophyllite free from admixture with any other phase by starting with a mixture of the oxides in the appropriate ratio, nor indeed by any other method. The significance of this fact is considered under the discussion of the stability regions of the several phases.

BRUCITE

Hexagonal plates of brucite, $Mg(OH)_2$, are readily obtained by hydration of MgO at appropriate temperatures and pressures. Of all the phases of the system it is, after forsterite, the best crystallizer, if size and perfection of crystals be the criteria. Brucite was also obtained by the serpentinization of forsterite; indeed the best brucite crystals were so obtained.

SILICA

In nearly all our experiments in which we obtained silica it appeared as cristobalite, whereas quartz is the stable form under the pressure-temperature conditions of all these runs. It is not unusual to obtain silica in a form that is metastable under the conditions in which it is produced. There are indications that the presence of other substances affects the tendency to assume the stable form. Growth in the presence of a vapor phase tends to promote persistence of the metastable forms and may be a governing factor in our runs. This appears to be true in natural occurrences also; cristobalite, for example, is formed at comparatively low temperatures in the vesicles of lavas.

Other factors appear to affect the form in which silica crystallizes in our runs. In one experiment MgO and SiO_2 were placed in separate crucibles in a platinum-lined bomb at 400°C and 15,000 lbs/in^2 pressure of water vapor. The silica crystallized completely as quartz, whereas if MgO and SiO_2 are mixed together in one crucible under these conditions any free silica that may remain in excess of the compound formed is always cristobalite. The effect of the presence of another substance is here plainly shown.

Much remains to be learned about such relations. We may note only that the stable quartz was obtained in the presence of magnesian phases in our runs only at

ELECTRON PHOTOMICROGRAPH OF CRYSTALS OF SYNTHETIC SERPENTINE
(Photograph by National Bureau of Standards)

TABLE 1.—*Critical determinations which fix position of univariant P, T-curves*

CURVE I

T(°C)	P (lbs/in²)	Initial Material	Time	Result
383	2100	FX**	18 hours	S+B
390	650	FX	3 days	F*
415	2000	FX	2 days	F
390	6000	FX	18 hours	S+B
420	6000	FX	2 days	F
425	15,000	FX	18 hours	S+B
450	15,000	FX	6 hours	F
425	22,500	FX	18 hours	S+B
425	28,000	FX	4 hours	S+B
442	28,000	FX	18 hours	F
446	40,000	FX	4 hours	S+B
460	40,000	FX	4 hours	F
365	15,000	Forsterite	2 weeks	S+B+F
		Olivine (Fo_{90}:Fa_{10})	2 weeks	No S
340	15,000	Forsterite	2 weeks	S+B+F
		Olivine (Fo_{90}–Fa_{10})	2 weeks	S+B+O(Mt)
		Olivine (Fo_{50}–Fa_{50})	2 weeks	No S (hematite)
295	15,000	Olivine (Fo_{50}–Fa_{50})	2 weeks	No S (hematite)

CURVE II

494	2000	SX	18 hours	S
510	2000	SX	18 hours	F+T
510	40,000	SX	5 hours	S
520	40,000	SX	5 hours	F+T
500	2000	Serpentine	18 hours	S
500	6000	Serpentine	3 days	F+T
485	15,000	Serpentine	18 hours	S
505	15,000	Serpentine	18 hours	F+T
505	22,500	Serpentine	18 hours	F+T
500	30,000	Serpentine	2 days	S
535	30,000	Serpentine	3 days	F+T

CURVE III

600	3000	EG**	3 days	T+F
600	6000	EG	18 hours	T+F
630	6000	EG	18 hours	E
650	15,000	EG	3 hours	T+F
670	15,000	EG	3 hours	E
650	23,000	EG	1 2/3 hours	T+F
670	22,500	EG	4 hours	E
675	30,000	EG	1 hour	T+F
690	30,000	EG	1 hour	E
650	22,500	E**	3 days	T+F
673	22,500	E	5 days	E

TABLE 1.—*Continued*

T(°C)	P (lbs/in²)	Initial Material	Time	Result
		CURVE IV		
755	6000	Talc	18 hours	T
775	6000	Talc	6 hours	E+C**
787	15,000	Talc	6 hours	T
800	15,000	Talc	6 hours	E+C
805	22,500	Talc	2 1/3 hours	T
820	22,500	Talc	6 1/2 hours	E+C
815	30,000	Talc	2 1/3 hours	T
835	30,000	Talc	2 1/3 hours	E+C
750	15,000	E+Q	13 days	T
		CURVE V		
880	6000	Brucite	2 1/2 hours	B
900	6000	Brucite	2 hours	P
880	1,5000	Brucite	3 hours	B
900	1,5000	Brucite	2 1/2 hours	P
880	1,5000	Periclase	3 hours	B

* Small amount of S and B present in some experiments, believed to be due to imperfect mixing.
** FX = a mixture of MgO and SiO_2 in the ratio corresponding with forsterite.
SX = a mixture of MgO and SiO_2 in the ratio corresponding with serpentine.
EG = enstatite glass.
C = cristobalite.
Other abbreviations are simply the initial letters of the names of the mineral phases as indicated in Figure 1.

the higher temperatures. Thus at 800°C we usually obtained more quartz than cristobalite. One might easily gain a false impression of the stability relations of the silica minerals from our runs, in which cristobalite ordinarily formed more readily at low and quartz at high temperatures.

EQUILIBRIA AND THE STABILITY REGIONS OF THE PHASES

GENERAL STATEMENT

It should be emphasized that all the equilibria studied in detail were vapor-crystal equilibria. No liquid phase was formed at any temperature and pressure at which we ordinarily carried on our investigations. A few runs were made at temperatures of 300°–350°C, and in these the aqueous phase could be appropriately referred to as liquid, but most of the work was carried on at temperatures where the aqueous phase could be described only as vapor, though at high pressures it was a vapor of high density. In Table 1 are given the details of all the runs that were critical in that they fixed the limits of stability regions that is, the positions of the curves. Many additional runs were made which fell in the middle of stability regions, and while these were confirmatory they were not critical and are therefore not listed.

The full story of our results is set forth in an equilibrium diagram (Fig. 2). For many readers some explanatory remarks are desirable. The diagram consists of a series of pressure-temperature curves of univariant equilibrium. Since the system is of three components univariancy requires the presence of four phases. Each

curve (except one) therefore refers to the equilibrium between three crystal phases and vapor. The one exception is curve V for the periclase-brucite-vapor equilibrium which refers to the limiting binary system, MgO—H_2O, and univariancy requires but three phases.

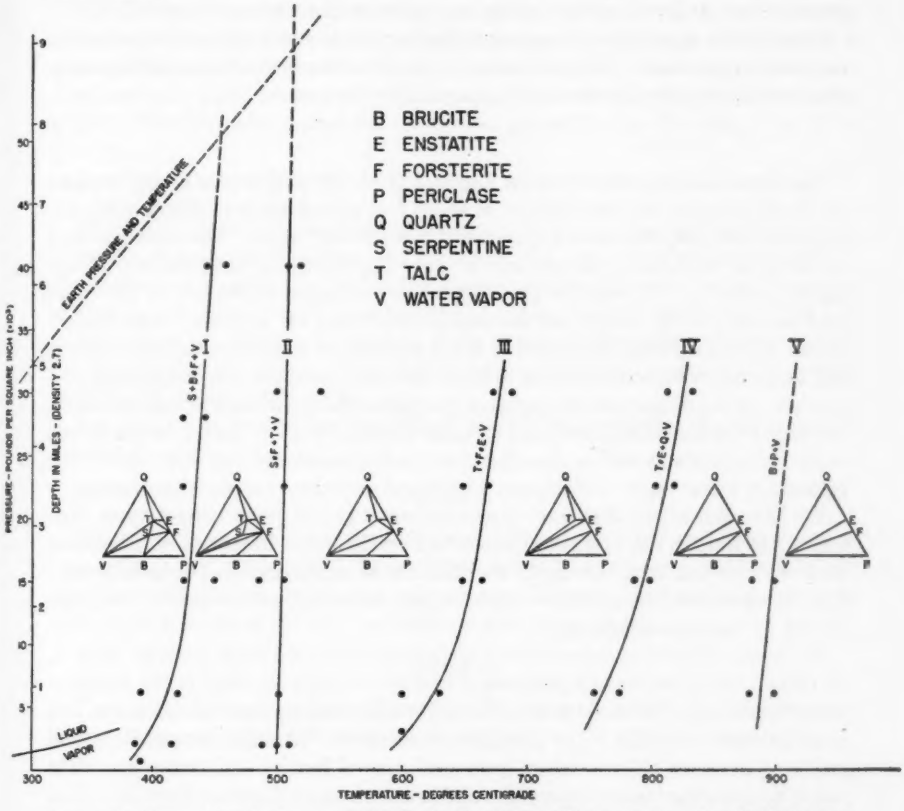


FIGURE 2.—*Pressure-temperature curves (I–V) of univariant equilibrium in the system MgO-SiO_2-H_2O*

Equation on each curve indicates the reaction to which the curve refers. Triangular diagram on each divariant region between curves indicates, for all compositions, the stable phase assemblages under the range of p,t-conditions represented by the region. Each heavy dot indicates the temperature and pressure of a critical experiment which fixes the position of a curve. Lower left—vapor-pressure curve of water ending at the critical temperature and pressure. Upper left—curve of normal earth pressure and temperature assuming a temperature gradient of 55°C/mi and a rock density of 2.7.

The curves separate fields or regions of divariancy where there can coexist at equilibrium one phase less than under the conditions of univariancy represented by the curves. In a three-component system these regions are therefore characterized by the coexistence of three phases, and the main triangle can therefore be subdivided into subsidiary triangles that indicate all possible equilibrium three-phase assemblages for the pressure and temperature ranges represented by any region. Such

a subdivided triangle thus constitutes an equilibrium diagram for the region. On each of the regions of Figure 2 is shown its appropriate equilibrium diagram. From it can be read the mineral constitution at equilibrium of any mass whose bulk composition is represented by any point in the main triangle, under conditions of temperature and pressure represented by any point in the region.

Some details regarding each curve and the manner in which the position was fixed may now be presented. This will naturally require reference to the equilibrium diagrams on the two contiguous regions separated by the curve.

CURVE I

The lowest-temperature curve on Figure 2 gives the temperature at any pressure (or the pressure at any temperature) at which four phases are in equilibrium according to the reaction, brucite + serpentine $\rightleftharpoons$ forsterite + vapor. The curve lies close to 400°C at the lower pressures and at only slightly higher temperatures at the higher pressures. The equilibrium diagram on the region to the left of the curve shows a line joining brucite and serpentine which cuts off forsterite from (water) vapor. The only phases that can exist in the presence of water vapor at any pressure and temperature represented by a point in this area are silica, talc, serpentine, and brucite. In the diagram on the region to the right of the curve the line joining brucite and serpentine has disappeared, and its place is taken by a line joining forsterite and vapor. Forsterite as well as the other four phases mentioned can now exist in the presence of water vapor. Moreover, brucite and serpentine can no longer coexist.

We have indications that there is another curve at still lower temperatures than Curve I at which a reaction takes place which results in the formation of sepiolite at the lower temperatures. Owing to the difficulty of identifying the products of reactions at these lower temperatures we have not carried out an exhaustive investigation of the sepiolite equilibria.

No details of the runs fixing Curve I are necessary beyond those given in Table 1. At certain temperatures and pressures a mixture of MgO and SiO_2 in the forsterite proportion always gave forsterite. The points representing these temperatures and pressures must therefore lie to the right of the curve. At other temperatures and pressures the same initial mixture gave a mixture of brucite and serpentine. The points representing these temperatures and pressures must therefore lie to the left of the curve. The curve is thus drawn between these two classes of points. It was also found that forsterite prepared in the dry way at high temperatures was serpentinized (giving brucite and serpentine) at temperatures below the curve but was unaffected at temperatures above the curve. Not until we had thus caused the reaction for this curve, and indeed all curves, to proceed in both the rising-temperature and the falling-temperature direction, were we satisfied that we were dealing with a reversible equilibrium.

CURVE II

This curve is the pressure-temperature curve of the equilibrium, serpentine $\rightleftharpoons$ talc + forsterite + vapor. On the diagram to the left of the curve there are three triangles which have the common apex, serpentine. These disappear, and their place

is taken on the diagram to the right of the curve by a single triangle. Serpentine cannot exist at temperatures above the curve. The departure of the curve from the vertical is small, and for all practical purposes it may be said that pure magnesian serpentine cannot exist at temperatures above 500°C.

The determinations which fix the curve are given in Table 1. The curve is located by finding a temperature at which pure synthetic serpentine remains unchanged at a given pressure of water vapor, and again a temperature at which serpentine is decomposed at a given pressure of water vapor. The curve must pass between these points. We have also caused the reaction to proceed in the direction, T + F + V → S.

CURVE III

This curve represents the temperature and pressure of the equilibrium, talc + forsterite ⇌ enstatite + vapor. To the left of the curve enstatite cannot exist in the presence of water vapor, and in the diagram on the region to the left these two phases are cut off from each other by the line joining talc and forsterite. This line disappears on the diagram to the right of the curve, and its place is taken by a line joining enstatite and vapor. Talc and forsterite can now no longer coexist, though individually they are still stable.

The curve was located by the method of bridging as already described for the preceding curves.

CURVE IV

This curve shows the upper limit of the stability of talc itself and gives the pressure-temperature conditions of the equilibrium, talc ⇌ enstatite + quartz + vapor. The three triangles having talc as a common apex disappear, and their place is taken by a single triangle on the high-temperature side of the curve.

CURVE V

The only hydrous phase that still survives is brucite. Curve V gives the pressure-temperature conditions of its dissociation according to the equation, brucite ⇌ periclase + vapor.

REGION ABOVE CURVE V

Under conditions represented by the area to the right of Curve V only anhydrous crystalline phases can coexist with water vapor. This area extends to the right until it encounters a curve which gives the equilibrium of crystalline phases with liquid and vapor, that is a curve of melting in the presence of water vapor. The exact position of this curve is not known, since it is beyond the temperature range of the pressure apparatus, but it probably lies at very high temperatures.

COMPOSITION OF THE VAPOR PHASE

No direct determination of the composition of the vapor phase was made, but very definite indications of its composition are available. As mentioned, an attempt was made to grow large crystals of serpentine by placing MgO and SiO_2 in separate

crucibles in a bomb with water vapor and permitting their slow reaction by transport in the vapor. Serpentine formed in the crucible which had contained only MgO, but only quartz formed in the crucible of SiO_2. In other words SiO_2 was transported in significant quantity, but no MgO was transported. The solubility of SiO_2 in water vapor under the pressure-temperature conditions prevailing is known to be not more than 0.1 per cent, yet it is capable of inducing, under the convective conditions prevailing in the bomb, a very significant transport. The solubility of MgO in the vapor must therefore be practically nil.

ABSENCE OF A STABILITY REGION FOR ANTHOPHYLLITE

In no diagram on Figure 2 is there any point indicating anthophyllite. Actually anthophyllite is obtained, usually in small amounts, together with the equilibrium phases under a wide variety of conditions. Anthophyllite as a major constituent was obtained in only one way, namely by heating talc for a short period under conditions represented by a point immediately to the right of Curve IV. The best conditions for this purpose were found to be 800°C and 15,000 lbs/in^2 and a duration of heating of 1 hour. This gives a product consisting of anthophyllite and silica. If the heating is continued the anthophyllite is itself decomposed into silica and enstatite, and in 3 hours no anthophyllite remains. Therefore, anthophyllite is formed only metastably as a step in the change from talc to enstatite and silica. Under other conditions of decomposition of talc just above Curve IV decomposition of the intermediate substance anthophyllite proceeds almost as rapidly as its formation. Accordingly the presence of anthophyllite cannot be verified with the microscope, but X-rays reveal its presence in small quantity together with enstatite and silica, except after a long run in which case only enstatite and silica are found.

At lower temperatures, where talc is stable, rare needles of anthophyllite are commonly found in the product of a run, but usually some part of each needle has been transformed to talc. Thus a needle may have segments that are talc, pseudomorphous after anthophyllite, alternating with segments of unchanged anthophyllite. It appears, in this case too, that anthophyllite develops as an intermediate phase in the formation of talc from anhydrous materials, just as it develops as an intermediate phase in the reverse process—namely, the dehydration of talc. We have found no conditions under which anthophyllite will persist and we can conclude only that pure magnesian anthophyllite has no stable range of existence in the presence of water vapor.

The closing phrase of the last sentence is an important one to bear in mind, for the experimental method here employed is capable of yielding only phases that can coexist with water vapor under the conditions of the experiment, provided the duration of the run is sufficient to insure equilibrium. In the two lower-temperature triangular diagrams of Figure 2 there could be a point for anthophyllite and two lines joining anthophyllite with silica and with forsterite respectively. Anthophyllite would thus be represented as a stable phase under the conditions of the region in which these diagrams lie. Anthophyllite would form in conditions where the total composition of a mass was such that there was insufficient water to convert the materials to the more hydrous phases talc and serpentine. There would be nothing

metastable about this relation just as there is nothing metastable about the enstatite that appears on these diagrams. Enstatite would form (or persist) if there were insufficient water for complete conversion of the substances to the more hydrous phases. So it might be with anthophyllite. However, in our experiments there is

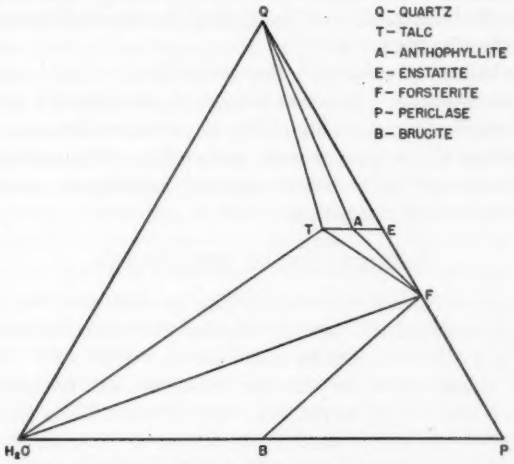


FIGURE 3.—*Not impossible form of equilibrium diagram for temperatures immediately above Curve II of Figure 2*

Shows anthophyllite as a stable phase in the absence of vapor (deficiency of water).

always an excess of water vapor. Therefore even if anthophyllite should appear on the two lower-temperature diagrams of stable equilibrium we would not obtain it as a persistent phase. The reason for omitting anthophyllite from the diagrams is that these vapor-absent relations come to light as we pass to higher temperatures. For example, in the lower-temperature diagram forsterite is shown as a vapor-absent phase. In our experiments at these temperatures we never get forsterite as a persistent phase; in fact, forsterite, initially present, is destroyed under these conditions. Nevertheless we know that forsterite must be on the diagram below Curve I in the relation there shown because it would otherwise be impossible to get the forsterite with the indubitable relation shown in the diagram above Curve I. Returning now to the anthophyllite question we find above Curve III enstatite and talc in equilibrium with each other and with water vapor. Anthophyllite is plainly nonexistent here as an equilibrium phase, for it is a simple binary compound between enstatite and talc. This means that anthophyllite must be absent also from the equilibrium diagram which obtains for the conditions immediately below Curve III.

It is still not altogether impossible that anthophyllite is stable at temperatures immediately above Curve II and that Figure 3 represents the equilibria there obtaining,[3] but if this is true another curve should appear between Curves II and III.

[3] The lines QA and FA would then appear on the two lower-temperature diagrams of Figure 2 also.

It would represent the binary equilibrium enstatite + talc $\rightleftharpoons$ anthophyllite. No vapor is involved in this reaction. Anthophyllite would then be stable only at temperatures below this other curve and would thus be a relatively low temperature mineral with a maximum temperature of existence considerably lower than the maximum temperature of existence of talc. It is very unlikely on this assumption that anthophyllite would be formed, even metastably, by the high-temperature decomposition of talc already discussed.

Therefore, the balance of evidence is that anthophyllite should not appear on any of the equilibrium diagrams. The pure magnesian anthophyllite should preferably be regarded as formed only metastably. This is not to be taken as even a suggestion that natural anthophyllites were formed metastably. They always contain significant amounts of other oxides which may and probably do render them stable under the conditions of their formation.

SIGNIFICANCE OF THE RESULTS

Attention may now be called to some petrogenic considerations that arise from our results. It is clear from the series of diagrams that forsterite is stable in contact with water vapor at all temperatures above Curve I (400° ca). Only below that temperature will water attack (serpentinize) forsterite, and the product is not serpentine only, but brucite and serpentine. The reaction takes place very slowly. Serpentine cannot be the sole product of the action of water on olivine. This has of course long been realized merely from the equation of the reaction. Olivine does appear to suffer a change in rocks whereby only serpentine remains in the rock. Unless the medium which induced serpentinization was capable of adding SiO_2 this means that the other product or products of serpentinization must be carried away. If silica is added, serpentinization of the olivine could take place at higher temperatures, but not above Curve II (500°ca) which is the upper limit of existence of serpentine. Serpentinization through addition of SiO_2 would be accompanied by a large increase of volume. Many geologists believe that the field relations indicate that no such increase of volume has ordinarily occurred.

Any medium that could carry away magnesia in any form might also induce serpentinization at a temperature above 400°, but that effect, naturally, would also be limited to temperatures below 500°. Above 500° a medium which could add silica or subtract magnesia could change forsterite only to talc or to talc and enstatite if the supply of water were deficient. Talc could form from forsterite at low temperatures also but only with intermediate formation of serpentine. Above Curve III (650°ca) the same medium would change forsterite to enstatite only, as a first step, and thereafter the enstatite would be changed to talc. Finally above Curve IV (800°ca) the same medium could change forsterite only to enstatite.

It is desirable, perhaps, to consider what would happen to a mass of molten forsterite in which some water was dissolved under a definite pressure equal to the superincumbent load. The mass would crystallize completely at a fixed temperature lower than the fixed temperature of crystallization of molten forsterite itself, but probably a very high temperature. At 1000°C, as our results show, the mass would consist only of forsterite crystals and water vapor. As it cooled no change would take place until about 400° where it would be slowly transformed into serpentine and brucite.

If instead of molten forsterite we had a molten mixture of forsterite and enstatite with some water dissolved, it, too, would consist only of crystals and vapor at 1000°. There woud now be two kinds of crystals, forsterite and enstatite. As it cooled further nothing would happen until Curve III was encountered (650°ca) when enstatite would be transformed to talc and a second generation of forsterite. At Curve II (500°ca) serpentine would form, and either forsterite or talc would be left in excess, unless the initial proportions of forsterite and enstatite happened to be just right to give serpentine only.

Turning now to the natural rocks and the application of these facts to them we may say that our results throw no light on the question of the possibility of the existence, under conditions beyond the scope of our experiments, of magmas approaching or attaining serpentine composition, but they do show that if such magmas exist they would be completely crystallized at 900°C to enstatite and olivine, and the water would occur entirely as vapor even at a pressure of 30,000 lbs/in^2.

In the possibility that this conclusion, based on results obtained with the purely magnesian compositions, might not apply to natural materials containing some iron, we have taken natural enstatite from Espedalen, Norway, containing 6.43 per cent FeO and olivine from Balsam Gap, North Carolina, containing 7.26 per cent FeO, ground them together to an extremely fine powder and subjected the powder to a temperature of 1000° and a water-vapor pressure of 15,000 lbs/in^2 for half an hour. The powder remained a powder which could be poured out of the crucible after the run. The only change in the mineral grains was the destruction of minute flecks of serpentine present here and there in the original grains. These were transformed to olivine and enstatite so that the net result was merely a cleaning up of the original material.

Our results seem to exclude the possibility of the intrusion at comparatively low temperatures of a magma of serpentine composition which crystallizes, wholly or in part, directly to serpentine. Many geologists believe that the field data indicate such an origin for serpentine. The more modern and systematically developed form of the hypothesis (Hess, 1938) postulates that there is early separation of olivine and pyroxene, but that they are transformed by their own highly aqueous mother liquor, an autoserpentinization. Other geologists believe field facts point to the formation of serpentine through introduction of solutions into a rock already completely crystallized to anhydrous minerals (olivine or olivine and pyroxene). This interpretation is in better accord with our experimental results.

EXPERIMENTS ON THE SERPENTINIZATION OF NATURAL OLIVINES

Many attempts have been made to effect serpentinization of natural olivines, usually without success, unless a reagent was added to the water used in the pressure vessel (Jander and Wuhrer, 1938). With water only, our results show that the pure forsterite cannot be serpentinized except below Curve I (400°ca). Earlier attempts with forsterite have usually been made at too high a temperature or have not been carried on long enough. Many former attempts were carried out with natural olivines containing iron. The usual failure is here even more markedly due to the attempt to effect the change at too high a temperature, for we have found that the iron-bearing olivines can be serpentinized only at still lower temperatures. Thus

at 365° and 15,000 lbs/in² olivine from North Carolina with 10 per cent fayalite molecule is not serpentinized in 2 weeks, though pure forsterite is definitely affected. At 340° and 15,000 lbs/in² the North Carolina olivine is definitely serpentinized in the same period. Curve I is thus lowered some 80° at this pressure if the olivine has 10 per cent fayalite. Hortonolite from Mooihoek with about 52 per cent fayalite is not serpentinized even at 295° and 15,000 lbs/in² pressure of water vapor. It may be doubted, indeed, that this hortonolite can be serpentinized at all, for at Mooihoek the hortonolite dunite is quite fresh at the outcrop, whereas the olivine dunite associated with it is serpentinized to a considerable depth, the serpentinization being there a low-temperature weathering phenomenon, though it is not usually such (Wagner, 1929).

In the experimental serpentinization of iron-bearing olivine some iron oxide was formed, just as it is when serpentinization takes place under natural conditions. The iron oxide formed from the North Carolina olivine was black and magnetic and therefore might be regarded as magnetite, $FeO \cdot Fe_2O_3$. However some flakes of iron oxide formed on the hortonolite, presumably as a result of abstraction of SiO_2, for it was not serpentinized, and these flakes were definitely hematite, Fe_2O_3. The two olivines had been exposed side by side to the action of water vapor in the same bomb. Given a certain partial pressure of oxygen in the vapor the temperature of transition from hematite to magnetite should have a fixed value, so that in any run one should get either hematite from both olivines or magnetite from both, if hematite and magnetite have a fixed composition. We conclude that the magnetite obtained from the highly magnesian North Carolina olivine was not pure iron oxide but had the composition $(Fe,Mg)O \cdot Fe_2O_3$.

ORIGIN OF DUNITE, SERPENTINE, AND RELATED INTRUSIVE ROCKS

That a special problem is posed by rocks of igneous aspect, that consist exclusively or almost exclusively of one mineral does not appear to have been realized until it was pointed out (Bowen, 1915, p. 79–80). Dunite is such a rock, and with it the problem is particularly acute. It is almost entirely olivine with no significant amounts of another mineral to give the mutual fluxing effect that ordinarily prevails in mineral assemblages. It could exist in the completely liquid state therefore only above the very high temperature at which olivine melts. In the absence of evidence of such very high temperatures at any stage of the existence of these rocks, it was suggested that dunite was never liquid as such but was formed by accumulation of early olivine crystals from a complex magma. It was also suggested that when the mass of olivine crystals thus accumulated was subjected to the appropriate forces it might be intruded into other rocks as a solid or substantially solid mass with little if any liquid to lubricate its flow (Bowen, 1917, p. 237).

Geologists have been, for the most part, reluctant to abandon dunitic or closely related liquid and have sought every avenue of escape from the fenced enclosure to which experimental studies appear to commit them. One by one these avenues have been closed by further experimental studies. Vogt (1921, p. 522) assumed that the fayalite molecule in dunitic olivine, though present in moderate amount, nevertheless effects drastic lowering of the melting temperature of forsterite, but laboratory in-

vestigation shows that olivine must have more than 70 per cent fayalite to bring its temperature of complete melting down to 1500°C (Bowen and Schairer, 1933, p. 393). Other assumptions have been made, the most important of which is that water is present in dunitic and related magmas in amounts sufficient to bring its melting range down to moderate temperatures, indeed to very low temperatures in some forms of this hypothesis. It is with this avenue of escape that we are principally concerned here.

As pointed out, even if a dunitic magma can exist containing large quantities of water—10 per cent or more—it probably could exist only at high temperatures and certainly, from our results, at a temperature above 1000°C. This is equally true of a hypothetical peridotitic magma having a composition equivalent to olivine plus orthopyroxene plus water and corresponding approximately or exactly with serpentine in composition. The possibility of the formation of dunites, serpentines, and peridotites from such supposed magma intruded *at low temperatures* is definitely excluded.

We shall avoid going into details regarding the various considerations that have been urged in favor of such intrusives. Instead we shall outline a hypothesis of the intrusion of such materials which is in accord with experimental results and, in our opinion, is not at variance with field facts.

Under certain conditions of crustal deformation, apparently involving strong overthrusting, dunitic and related material, coming at times perhaps from a peridotite shell of the earth, at other times from a peridotite mass that has formed as a differentiate of gabbroid magma, can be intruded in a completely crystalline state into accessible levels of the earth. It may be that an olivine aggregate is more capable of flow in the crystalline state than other common anhydrous rock-forming minerals, because its crystals are built up of SiO_4 groups without any chain, double chain, sheet, or space linkages—*i.e.*, sharing of O atoms by Si atoms. However this may be, the field facts indicating low temperatures, together with our experimental results, preclude the belief that the material is in the form of magma. There is no reason to suppose that the crystalline mass initially has more than traces of water. If, as it moves slowly under the deformative forces, the mass comes into a zone of wet rocks it may acquire water from those rocks, as Hess (1938, p. 331) has suggested. Above 500°, or even above 400° if it is a mass of olivine only, the amount of water that can enter the mass will be merely that which can exist as vapor in the pore spaces and minute fractures of the crystal aggregate which is suffering gliding translations and perhaps also granulation and some major fracturing. The vapor so existing may greatly facilitate the flow of the mass after the manner suggested by Sosman (1938). The temperature of the mass will depend on its temperature before it started to migrate and on the rate of migration, because the frictional effects attendant upon its motion will necessarily be a source of heat. If the temperature of the mass when it comes into wet surroundings is below 500° no change in the condition pictured will occur in an olivine mass, but serpentinization will begin in a mass consisting of pyroxene and olivine, and now the water which is driven into the mass from its wet environs will be consumed by this reaction, and more water will enter to take its place. A mass peripherally serpentinized but centrally unchanged would not be an

unexpected result of such action. The serpentine formed has such mechanical properties that continued deformation and intrusion of the mass will be greatly facilitated, and typical intrusive serpentine masses may develop.

If the initial mass were pure olivine it would develop serpentine under like conditions only when its temperature was below 400°, and further movement and intrusion would then be facilitated. With the serpentine there would now necessarily be developed brucite also.

The foregoing statements are based on the action of pure water, the only medium we have investigated. The aqueous medium coming into the mass in nature would not be pure water. The restriction of the formation of serpentine to temperatures below 500° would still obtain, but the possibility of the formation of serpentine from olivine alone up to this maximum temperature of existence of serpentine would now enter the picture. Thus if CO_2 were present and formed a moderately soluble carbonate with the excess magnesia, which was thereby removed, serpentine could be formed up to 500°. The same result would be obtained if the aqueous medium could add SiO_2 to the mass. In this case very great increase of volume would result.

The foregoing discussion is not to be taken as indicating an opinion that a still-standing mass of ultrabasics cannot suffer serpentinization. It is intended more to suggest the conditions under which independent intrusive masses of peridotite and serpentine can come into being. Nevertheless the mechanism described may be particularly effective in producing pervasive serpentinization. A still-standing mass of dunite or peridotite, might not be as readily serpentinized through and through.

An ultramafic mass of this type would come into being at the temperature at which accumulation of its constituent crystals took place from a mafic magma, probably between 1100° and 1200°C. It is very difficult to picture any mechanism whereby such a mass can suffer serpentinization by autometamorphism. There is presumably, at the highest temperatures, a superincumbent mass of still-liquid mafic magma. This liquid will have some water dissolved, but with continued cooling and accumulation of more and more crystalline material above the ultramafic the water tends to remain in the still-liquid portion which is confined to progressively higher and higher levels. The nearest approach to autometamorphism that can be conceived in this situation is the metamorphism of the ultramafics by the water in the later residual liquids of the whole mass, which, when they eventually come into being, are spatially removed and mechanically separated from the ultramafics in a very effective manner. It is very unlikely that these residuals could ordinarily have access to the ultramafics. On the basis of these considerations it would seem that we must look to a totally extraneous source for the aqueous media inducing serpentinization in ultramafics of this type.

It may be of value to state what our results indicate regarding the behavior of such an ultramafic differentiate of a mafic magma if there were free access of water as it cooled from its temperature of formation at 1100–1200°. In a mass consisting of olivine and orthopyroxene the latter mineral would be the first affected. It would be changed to talc in the neighborhood of 650°, but talc formation would be accompanied by the growth of a second generation of olivine. Near 500° talc and olivine would react with each other and with water to give serpentine, leaving an excess of

either talc or forsterite unless they happened to be present in equivalent quantities. If talc were in excess there would be no change with further cooling. With olivine in excess serpentine and brucite would develop from it around 400° or lower. With the natural iron-bearing minerals there would, of course, be formation of magnetite upon appearance of the hydrous minerals, but this is a detail of no moment.

A cumulate mass consisting entirely of olivine crystals would suffer the last change only.

These statements require some modification to embrace the possibility of the formation of anthophyllite in natural rocks, a phase which does not form in the pure magnesian materials except as a passing phenomenon. Even taking count of such differences between the natural and the synthetic materials the effects outlined above are so different from the effects ordinarily seen in rocks that it seems necessary to conclude that such rocks are not ordinarily metamorphosed in the cooling cycle during which they first came into being. It is much more likely that they usually cooled without significant metamorphism and were later subjected to hydrothermal metamorphism and reheating, due to solutions of extraneous origin which were capable of introducing certain substances and of carrying others away. Lest this be regarded as the conclusion of laboratory workers who know nothing about the rocks in the field we quote the conclusion of a field geologist to remind our readers that not all field geologists accept the autometamorphic origin of serpentine. Du Rietz (1935, p. 233) writes: "In the regions described by the writer no facts supporting the derivation of the serpentinizing solutions from peridotite magmas were observed."

Though the tendency toward uniform serpentinization of all the minerals of the ultramafics indicates that serpentinization has usually been the work of solutions of extraneous origin which have probably reheated the peridotite, it is likely that upon occasion conditions have been right for serpentinization during the cooling cycle. It is only necessary that an aqueous medium be available during the cooling cycle. In this case, too, it will be, we are forced to conclude, of extraneous origin. Rocks in which talc occurs as pseudomorphs after enstatite crystals are probably so formed, if the indications of our experiments are to be relied upon. In the cooling cycle, it will be recalled, enstatite goes to talc while olivine is still unaffected. Later the olivine is serpentinized. This is probably what has occurred in the ultramafics carrying these talc pseudomorphs (Du Rietz, 1935, p. 151). In the usual example of serpentinization both olivine and orthopyroxene go to serpentine, but the orthopyroxene is the more resistant, and some of it may survive unchanged when the olivine is completely replaced. This strongly suggests reheating of a "fresh" ultramafic and serpentinization at a very low temperature where the metasilicate is much more resistant to change than the orthosilicate.

TRANSFORMATION OF SERPENTINE INTO HIGHER-GRADE PHASES

We may note also that reheating may be carried to such an extent that the serpentine formed at low temperatures is subsequently changed to higher-grade phases. According to the indications of our experiments it should change first to olivine plus talc, a change which appears to have taken place in remote zones of the metamorphic aureoles of quartz diorite stocks intrusive into serpentines in California. Macdonald

(1942, p. 244) says:

"It seems reasonably certain that the olivine in these rocks has been regenerated in the course of metamorphism . . . essentially thermal in nature. . . . The grains of olivine are quite commonly poikiloblastic, enclosing smaller grains of serpentine, talc and iron ore."

This change would probably occur in the natural iron-bearing minerals at a lower temperature than 500° (Curve II) just as we have found experimentally that the temperature of Curve I is lowered in iron-bearing phases. In inner zones of such aureoles serpentine has been changed to a yet higher-grade rock, a hornfels composed of olivine, hypersthene, bornblende, spinel, and clinochlore (Durrell, 1940, p. 83). Some of these minerals are just those to be expected if the temperature was raised above that of Curve III as modified in the presence of iron, but here there are additional complications connected with the presence of notable amounts of Al_2O_3 also, perhaps in part introduced from the intrusive.

Thermal metamorphism induced by intrusive bodies may not be the only means of transforming serpentine into higher-grade phases. In the intrusion of a mass of solid serpentine which we have postulated, it might be supposed that, if acted upon by forces of sufficient intensity to move it at a fairly rapid rate, the mass would be heated frictionally to a sufficient degree to raise it to a temperature where serpentine would not be stable, or it might be that only the border zones of the moving mass would be sufficiently heated in this manner to suffer change while the interior remained unchanged. Thus might be produced a mass with a serpentine core and a peridotite border, the opposite situation to that discussed earlier.

The dunite-mylonites of St. Paul's Rocks described by Tilley (1947) represent dunitic material from a deeper layer which has probably been pushed up as a solid mass and at such a rate that minute granulation resulted. While moving it was always kept at a sufficiently high temperature that no serpentinization could occur even though it probably moved through wet surroundings. When it came to rest it quickly became a well-knit mass, free from significant channels and minute fractures and therefore offered no access to water as it cooled through the range where serpentinization could have taken place.

The mylonization was no accidental feature but was a necessary accompaniment of movement of the dunite to its present position.

TECTONIC SETTING OF SERPENTINE AND RELATED INTRUSIVES

All the facts that Hess points out regarding the loci of intrusions of his "ultramafic magma series" appear to be of a kind which lends color to the concept that the material was actually intruded in the solid state. He says of the West Indies: ". . . the belt of serpentinized peridotite intrusions lies adjacent to the band of strongly negative anomalies marking the most intense zone of deformation" (Hess, 1938, p. 332–333). Again in his splendid study of island arcs in the North Pacific he finds evidence of the same general situation. Here the deformation is rather definitely decipherable as a 45-degree shear on which are located the foci of deep earthquakes (Hess, 1948). The Serpentine Belt of Australia has long been known to be associated with a great overthrust, and the same relations are now known to exist for the serpentines of Cuba (Thayer and Guild, 1947). Our work indicates that

the intrusive would be olivine plus orthopyroxene during its movement if it was maintained at a high temperature; if the temperature was intermediate, it would be olivine plus talc; if the temperature was low it would be serpentine, provided there was access of water at all temperatures. In the absence of a supply of water it would be olivine and pyroxene at all temperatures, but in such case it might not be significantly mobile at low temperatures.

LIMIT OF CRUSTAL EXISTENCE OF SERPENTINE

Serpentine cannot be present in any layer of the earth's crust whose temperature is normally above the decomposition temperature of serpentine under the pressure prevailing. In Figure 2 we have drawn a line indicating the normal pressure-temperature conditions in the earth, assuming an average density of rocks of 2.7 and a geothermal gradient of 55°/mi (Landsberg, 1946). This line intersects Curve II at a depth of a little less than 9 miles where the temperature is a little above 500°C. Below that depth serpentine could not exist. We wish to emphasize that the nonexistence of serpentine below that level cannot be attributed to the fact that the pressure is so great that water is squeezed out of the serpentine crystal lattice. On the contrary the high pressure tends to make the hydrous phase serpentine stable, but the temperature has become so high that the effect of pressure is over-balanced and the serpentine decomposes into talc, forsterite, and water vapor, an assemblage having greater volume than the serpentine.

The line indicating earth pressure and temperature intersects Curve I at a depth somewhat less than 8 miles. Below that depth the assemblage serpentine plus brucite would be unstable, and its place would be taken by olivine. Any excess of serpentine above that needed for the reaction would persist with the olivine down to the depth already pointed out as that below which the serpentine must disaapper.

MUTUAL RELATIONS OF VARIOUS ROCK TYPES IN ULTRAMAFIC COMPLEXES

In an ultramafic complex it is not unusual to find pipes and dike-like masses of one rock type in another, that have been interpreted as indicating intrusion of the material of the pipe or dike as a liquid magma. Sometimes the age indications afforded by these "intrusives" are contradictory; that is, pyroxenite dikes may cut dunite, and dunite may cut pyroxenite, all in the same mass. Some observations made in the course of our experiments suggest the possibility of an interpretation of these relations other than that ordinarily given.

On an earlier page we pointed out that silica was abstracted from some of our charges by water vapor and that when it was imperative that no change of composition of the charge should occur special precautions were necessary to prevent this transport of SiO_2. The loss of SiO_2 can occur even when no free SiO_2 is present. Thus after heating synthetic enstatite at 725°C and 22,500 lbs/in^2 pressure of water vapor for 2 days it was found that some of the enstatite was transformed to forsterite, when no precautions were taken against removal of silica by water vapor. It seems possible, therefore, that if a crack formed in a mass of rock consisting mainly of orthopyroxene, and if water vapor unsaturated with SiO_2 streamed through the crack the rock adjacent to the crack could be converted to a type consisting mainly

of olivine, which might appear to be a dike in the pyroxenite. A fracture zone serving in the same capacity as the postulated crack might become a pipe of dunite.

It has also been shown on an earlier page that SiO_2 and other substances (*e.g.*, iron oxide) can be transferred to our charge by water vapor. In many runs made without buffer we found a crust of needles of clinohypersthene on the surface of our charge. Their development was possible only through addition of silica and iron to the charge. In the light of these observations it seems possible that water vapor charged with SiO_2 and other substances and streaming through a crack in peridotite could convert the adjacent rock to pyroxenite having a dikelike relation.

In short our observations suggest that the mutual "intrusion" of ultramafic types in such complexes, often giving contradictory indications of time of "intrusion," is really due to hydrothermal (pneumatolytic) rearrangement of material, taking place largely within the mass itself, though the water and perhaps small amounts of other substances were of extraneous origin.

Such "intrusives" would not extend beyond the borders of the ultramafic complex, and this appears to be the relation observed.

REFERENCES CITED

Bowen, N. L. (1915) *The later stages of the evolution of the igneous rocks*, Jour. Geol., vol. 23, no. 8 Suppl., 91 pages.

——— (1917) *The problem of the anorthosites*, Jour. Geol., vol. 25 p. 209–243.

——— and Andersen, Olaf (1914) *The system MgO—SiO₂*, Am. Jour. Sci., vol. 37, p. 487–500.

——— and Schairer, J. F. (1933) *The problem of the intrusion of dunite in the light of the olivine diagram*, XVI Int. Geol. Cong., Rept., vol. 1, p. 391–396.

Du Rietz, T. (1935) *Peridotites, serpentines and soapstones of northern Sweden*, Geol. Fören. Stockholm, Förh., no. 401, Bd. 57, H. 2, p. 135–260.

Durrell, Cordell (1940) *Metamorphism in the southern Sierra Nevada northeast of Visalia, California*, Univ. Calif., Dept. Geol., Bull., vol. 25, p. 1–117.

Hess, H. H. (1938) *A primary peridotite magma*, Am. Jour. Sci., 5th ser., vol. 35, no. 20, p. 321–344.

——— (1948) *Major structural features of the western north Pacific; An interpretation of HO 5485 Bathymetric Chart, Korea to New Guinea*, Geol. Soc. Am., Bull., vol. 59, p. 417–446.

Jander, W., and Wuhrer, J. (1938) *Die Bildung von Magnesium-hydrosilikaten*, Zs. für anorg. Chemie, Bd. 235, p. 282–287.

Landsberg, H. (1946) *Note on the frequency distribution of geothermal gradients*, Am. Geophys. Union, Tr., vol. 27, p. 549.

Macdonald, G. A. (1942) *Geology of the western Sierra Nevada between the Kings and San Joaquin rivers, Calif.*, Univ. Calif., Dept. Geol., Bull., vol. 26, p. 244.

Morey, G. W., and Ingerson, Earl (1937) *A bomb for use in hydrothermal experimentation*, Am. Mineral., vol. 22, p. 1121–1122.

Sosman, R. B. (1938) *Evidence on the intrusion-temperature of peridotites*, Am. Jour. Sci., 5th ser., vol. 35A, p. 353–359.

Thayer, T. P., and Guild, P. W. (1947) *Thrust faults and related structures in eastern Cuba*, Am. Geophys. Union, Tr., vol. 28, p. 919–930.

Tilley, C. E. (1947) *The dunite-mylonites of St. Paul's rocks (Atlantic)*, Am. Jour. Sci., vol. 245, p. 483–491.

Tuttle, O. F. (1948) *A new hydrothermal quenching apparatus*, Am. Jour. Sci., vol. 246, p. 628–635.

Vogt, J. H. L. (1921) *The physical chemistry of the crystallization and magnetic differentiation of igneous rocks*, Jour. Geol., vol. 29, p. 522–539.

Wagner, P. A. (1929) *Platinum deposits and mines of South Africa*, Oliver & Boyd, Edinburgh, p. 55, 77.

GEOPHYSICAL LABORATORY, 2801 UPTON STREET, WASHINGTON 8, D.C.

MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, JULY 8, 1948.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 60, PP. 461–530, 28 FIGS. MARCH 1949

SUBSIDENCE IN THE LONG BEACH HARBOR AREA, CALIFORNIA

BY JAMES GILLULY AND U. S. GRANT

CONTENTS

	Page
Abstract	463
Introduction	464
Distribution and amount of elevation changes in the Long Beach area	464
General statement	464
U. S. Coast and Geodetic Surveys	465
History of surveys	465
Elevation changes shown by the adjustments of 1928 and 1931–1932	465
Elevation changes shown by the surveys of 1931–1932 and 1933–1934	466
Elevation changes show by the surveys of 1933–1934 and 1941	469
Elevation changes shown by the surveys of 1941 and 1945	471
Elevation changes shown by the survey of March 1946	471
Long Beach Harbor Department surveys	473
Surveys by the Long Beach City Engineer's Office	475
Surveys by the Los Angeles County Surveyor	476
Surveys by the U. S. Navy	476
Surveys by the Los Angeles County Sanitation Districts	477
Tide gauge comparisons	478
Summary of elevation changes	481
Geology of the Wilmington oil field and adjacent areas	482
Preliminary statement	482
Stratigraphy and structure	482
General conditions	482
Shallower strata	483
Oil zones	485
Field development	487
Possible causes of subsidence	487
Preliminary statement	487
Tectonic movements	488
Introduction	488
Geological setting	488
Geological inferences from survey data	491
Lurching, slumping, and landsliding	491
Horizontal movements	492
Tilting due to differential subsidence	492
Summary	493
Effects of changes in ground-water regimen	494
Introduction	494
Effect of ground water disturbance in 1941	494
Regional changes in regimen of confined ground water	497
Effect of water-table fluctuations	499
Influence of increased loads on the surface	500
Effect of oil-field operations	501
Introduction	501

Page
Relation of subsidence to volume of oil removed 501
Relation of subsidence to loss of pressure in oil sands 502
Other examples of subsiding oil fields 525
Addendum 527
References cited 527

ILLUSTRATIONS

Figure
1.—Elevation changes in the Long Beach area shown by leveling by the U. S. Coast and Geodetic Survey, adjustments of 1928 and 1931–1932 467
2.—Elevation changes in the Long Beach area shown by leveling by the U. S. Coast and Geodetic Survey in 1931–1932 and 1933–1934 468
3.—Elevation changes in the Long Beach area shown by leveling by the U. S. Coast and Geodetic Survey during 1933–1934 and June–July 1941 470
4.—Elevation changes in the Long Beach area shown by leveling by the U. S. Coast and Geodetic Survey in 1941 and 1945 472
5.—Elevation changes in the Long Beach area between 1933–1934 and March 1946 473
6.—Elevation changes in the Long Beach Harbor area between 1924 and January 1, 1945 474
7.—Elevation changes in the Long Beach Harbor area, 1924 to 1945 475
8.—Subsidence between Reeves Field and Naval Drydocks on Terminal Island, from November 1943 to March 1945 477
9.—Graph showing rate of subsidence between November 1943 and March 1945 of a bench mark in the Naval Drydock area of Terminal Island as compared to B. M. K-97, at Reeves Field 478
10.—Marigram of tide gauge of Long Beach Outer Harbor, compared with that of Los Angeles Outer Harbor, 1925–1946 479
11.—Subsidence of water-intake at Southern California Edison Company Steam Plant 480
12.—Subsidence of General Petroleum Corporation Tide Gauge, at the east entrance, Ford Slip, Long Beach Inner Harbor, 1938–1945 481
13.—Generalized geologic section, Terminal Island toward Dominguez Gap 484
14.—Water-level fluctuations and elevations of representative bench marks near the Southern California Edison Company Steam Plant during the dewatering of the near-by U. S. Navy Graving Dock, June 1941–April 1942 495
15.—Chart showing relation between depth of a column of porous sediments and the pressure exerted on its base (the underlying strata) 504
16.—Structure contours on the "F" marker, Ranger zone, Wilmington oil field 505
17.—Isopleth map showing distribution and amount of reduction in pressure in the "Ford" zone, Wilmington oil field, to January 1, 1945 506
18.—Isopleth map showing distribution and amount of reduction in pressure in "Terminal" zone, Wilmington oil field, to January 1, 1945 506
19.—Isopleth map showing distribution and amount of reduction in pressure in "Tar-Ranger" zone, Wilmington oil field, to January 1, 1945 507
20.—Isopachs showing approximate length of perforated casing (thickness of zone of reduction of fluid pressure) of the "Ford" zone, Wilmington oil field 508
21.—Isopachs showing approximate length of perforated casing (thickness of zone of reduction of fluid pressure) of the "Terminal" zone, Wilmington oil field 509
22.—Isopachs showing approximate length of the perforated casing (thickness of zone of reduction of flluid pressure) of the "Tar-Ranger" zones, Wilmington oil field 510
23.—Stress-strain relations under compression of sandstones from the several oil-zones, Wilmington oil field 512
24.—Theoretical subsidence in the Wilmington oil field to January 1, 1945, due to pressure decline within the "Ford" zone only 515

Figure Page
25.—Theoretical subsidence in the Wilmington oil field to January 1, 1945, due to pressure decline within the "Terminal" zone only 516
26.—Theoretical subsidence in the Wilmington oil field to January 1, 1945, due to pressure decline in the "Tar-Ranger" zone only 517
27.—Total theoretical subsidence in the Wilmington oil field due to pressure decline in all zones to January 1, 1945 517
28.—Representative casing programs employed in the Wilmington oil field 520

ABSTRACT

Surveys and other observations in the area of Long Beach Harbor, California, indicate a general subsidence over a large area. Over the near-by plain to the north and east of the harbor, this subsidence averages a few tenths of a foot over a period of about 20 years. In this larger field of subsidence there is a localized area within which the depression of the surface amounts to several feet, reaching a maximum of more than 4 feet[1] in the region of the Inner Harbor. This area of maximum subsidence, when contoured according to available level data, coincides remarkably with the productive area of the Wilmington oil field. It is also highly significant that the subsidence, as indicated by tide-gauge records, first became notable in 1937, shortly after the beginning of the development of the field.

The following possible causes of the subsidence have been considered:

Tectonic—earthquakes, horizontal and vertical movements in the earth's crust, faults, tilting.

Decline of pressure in water sands, lowering of the water table.

Increased loads due to structures and fill deposited on the surface.

Oil-field operations, including removal of oil from underground, decline of pressure in the oil reservoirs, with resulting increased load on them, and elastic shortening and plastic deformation expected therefrom.

The possible effect of each of these factors is discussed, together with data on the mechanical properties of the oil sands.

Conclusions reached are:

(1) A very small part of the subsidence—perhaps a few tenths of a foot—may possibly be due to tectonic movements but is not certainly so. It is equally likely to be due to decline of water pressure in aquifers underlying the whole region or, in part, to loss of reservoir pressure due to flow of water in the oil sands to neighboring oil fields.

(2) The excessive subsidence localized within the Wilmington oil field is primarily the result of oil-field operations. Reasons for excluding tectonic factors from responsibility are summarized. There is no correlation between the amount of oil production from a given part of the field and the amount of subsidence there, when areas as large as a "production block" (about half a square mile) are considered. There is some correlation between subsidence and production in areas of intensive exploitation, but this is believed to be indirect and dependent upon the influence of pressure decline on both processes. On the other hand, there is a very close agreement between the relative subsidence of the various parts of the field and the pressure decline, thickness of oil sand affected, and mechanical properties of the oil sands. This correlation is so close as to constitute conclusive evidence of a cause and effect relation between pressure decline and subsidence.

An accurate forecast of the amount of ultimate subsidence is impossible. In part it is dependent on the rate of production of oil and gas from the field, for the pressure drop in the reservoir sands may be expected, over a long time, to parallel

[1] In February 1947, after this study had been completed, the maximum subsidence had reached 5.98 feet, according to R. R. Shoemaker.

this production rate. Although the current rate of subsidence is higher than the rate of pressure decline, this will probably eventually slacken, so that it may require 8 or 10 years for the subsidence of another 4 feet, and the ultimate subsidence to be expected if the production of the oil field proceeds to depletion is estimated at about 10 feet. This amount will not, however, be reached over the entire field, but is expected to be limited approximately to the present area of maximum subsidence. From this area the subsidence will diminish in all directions, so that, though the area affected by considerable sinking will eventually be somewhat larger than that now involved, the amount of subsidence will not be more than about two to three times that which has already taken place. In other words, the ultimate isobase of 1 foot subsidence may be expected to be near the present isobase of .50 foot subsidence. These estimates of ultimate subsidence are predicated upon continued exploitation of the oil field and will not be realized should production be substantially curtailed or stopped. On the other hand, should additional oil zones be discovered and produced, the above estimate would have to be increased because of contraction of the additional oil sands.

INTRODUCTION

Minor changes in elevation of bench marks in the Long Beach, California, area appear whenever the results of two surveys a few years apart are compared. Most of these changes amount only to a few tenths of a foot and though of considerable theoretical interest, as they commonly exceed the reasonable limits of surveying error, are not economically important. Beginning in 1937, however, a considerable area of Terminal Island and the adjacent mainland began to subside at a higher rate. By January 1945 the maximum subsidence had amounted to nearly 4 feet. As the land is low and in fact some of it fill, through which channels have been dredged for wharves, the freeboard of the docks decreased notably, and many harbor installations required adjustment. It thus became of interest to the Board of Harbor Commissioners of Long Beach to ascertain, if possible, the cause of the subsidence and to estimate its future extent and amount. The writers, in association with Mr. Harry R. Johnson, were asked to investigate the questions.

It is a pleasure to acknowledge the co-operation of Mr. R. R. Shoemaker, Chief Engineer, Messrs. C. L. Vickers, Frank Hardesty, M. D. Hughes, and Roy H. Baldridge of the Engineering Office of the Harbor Board of Long Beach, of Mr. W. L. Chadwick, Manager, and Mr. R. W. Spencer, of the Engineering Department of the Southern California Edison Company, of Mr. H. R. Johnson and his associate Mr. Willard W. Cutler, Jr., of our colleague Professor Wendell Mason of the Department of Engineering, and Commander R. R. Lukens of the U. S. Coast and Geodetic Survey.

DISTRIBUTION AND AMOUNT OF ELEVATION CHANGES IN THE LONG BEACH AREA

GENERAL STATEMENT

Data relating to elevation changes in the Long Beach area are derived from: precise leveling at various times by the U. S. Coast and Geodetic Survey, levels by the Long Beach City Engineer, the Long Beach Harbor Department, the Los Angeles County Surveyor, the U. S. Navy, and the Los Angeles County Sanitation districts; and by intercomparison of tide gauges between Long Beach Harbor and San Pedro.

With a few exceptions, to be mentioned below, these data on elevation changes are sporadic and, while permitting intercomparison of individual bench marks at various times, fail to give a homogeneous picture of the changes over the whole area affected. All the information available to us is presented in this report; to present the general picture, which most of the other data merely amplifies, the various surveys of the U. S. Coast and Geodetic Survey are discussed first.

U. S. COAST AND GEODETIC SURVEYS

History of surveys.—First-order leveling by the Coast Survey was begun in this area in 1906, and further work was done at various times in 1920, 1925, 1926, and 1927 (U.S.C.G.S., 1941). Adjustment of levels taken at such widely different times in this unstable area probably conceals changes in elevation which, as will appear from intercomparison of later surveys, almost surely occurred during this period of 20 years. The 1928 adjustment by the Coast Survey, in which the surveys of these prior years were treated, is probably thus not comparable with later surveys as to homogeneity of data. In fact, this adjustment is not referred to in the pamphlet cited. In 1931–1932 the entire net of the Coast Survey in the area was resurveyed.

The results of the survey of 1931–1932 were adjusted and are recorded as *Southern California supplementary adjustment of 1934* (U.S.C.G.S., 1941). After the Long Beach earthquake of March 10, 1933, the lines in the Long Beach area were rerun. Adjustment of this survey was made by holding fixed the elevations determined by the *Supplementary adjustment of 1934* for the following bench marks: 955 (U.S.G.S.) at Girard, V 96 at Los Angeles, various bench marks between Colton and Hinda, M 38 at Arlington, Tidal 1 at Balboa, and Tidal 8 at San Pedro. The adjusted elevations resulting from this survey are given (U.S.C.G.S., 1941) under the heading "Adjusted Elevation, 1933–1934 Re-leveling," and in parallel columns with the elevations of the 1931–1932 Survey, thus facilitating comparison.

In order to study earth movements reported in this area, the Coast Survey releveled a part of the network in the vicinity of San Pedro, Wilmington, and Long Beach between June 13 and July 25, 1941. This leveling was adjusted by holding fixed the following bench marks: Tidal 8, (San Pedro), R 50 (Manhattan Beach), Y 96 (Florence), and H 51 (Long Beach) (U.S.C.G.S., 1943).

The Coast Survey again releveled the bench marks in this area during the summer of 1945. Although the final results have not been published, unadjusted elevations have been made available through the courtesy of Commander R. R. Lukens and are used in this report. Commander Lukens (oral communication) believes that the adjusted figures will not differ significantly from the preliminary figures here used. The Coast Survey also repeated a single line of precise levels along Seaside Boulevard during the spring of 1946, and these data have been used to guide the isobase map (Fig. 5), showing the most recent precise information for the area.

Elevation changes shown by the adjustments of 1928 and 1931–1932.—The level work of the Coast Survey prior to 1928 was adjusted in that year. The adjustment disregarded the differing stabilities of the various bench marks and thus does not recognize the crustal movements or other changes of surface levels during the period between the first leveling in 1906 and the date of the adjustment. The elevations

of bench marks given in this adjustment have been readjusted by Mr. R. H. Baldridge, of the Long Beach Harbor Department, to an elevation of 11.129 feet for B. M. Tidal 8, San Pedro. In Figure 1 the locations of the bench marks, elevations of which are available for 1928 and for 1931–1932, are shown together with isobases determined from the ostensible changes in level that occurred in the interval.

This map is not comparable with Figures 2 and 3 because of the uncertainty introduced by adjusting, in one net, surveys taken over a period of 21 years. It does, however, establish the fact that elevation changes occurred in the area prior to the Long Beach earthquake. Though the data are few and not well spaced, it can be seen that a general subsidence took place in the Long Beach area during this interval and that its maximun was near Signal Hill. It is unfortunate that comparison for this period cannot be made of bench marks near the present area of maximum subsidence, but, insofar as this map shows, B. M. B 51, at Alameda Avenue, on Anaheim Street (which the 1941 Survey shows to have subsided more than any other on that street) subsided much less than did bench marks farther east. So far as it goes, then, this figure shows a pattern of subsidence notably different than that of later surveys.

Elevation changes shown by the surveys of 1931–1932 and 1933–1934.—The bench marks for which elevations were determined during both these surveys are shown on Figure 2. Using these control points, isobases have been drawn at intervals of .050 feet. Plus indicates an increase in elevation between the two surveys; minus indicates a decrease. The Long Beach earthquake of March 10, 1933, took place in the interval between these surveys, and ground movement at the time of the quake ruptured pavements and displaced curbings at many points in the area.

Changes of elevation between these surveys are of two types: (1) localized changes involving areas of less than 2 square miles, and (2) broadly distributed changes affecting a very much larger area. Changes of the first kind are, of course, less certainly significant than are those of the second. Marked discrepancies in the readings on a single bench mark may reflect only a local lurching of the ground or, indeed, may result from errors in one or both of the surveys. Such explanations could not reasonably apply to changes affecting a large number of widely distributed bench marks, especially if these changes are systematic.

Local Changes: A local anomaly in elevation was shown by B. M. 38 (L. A. H. D.) in San Pedro, located in the southwest corner of the concrete viaduct on Harbor Boulevard that leads to the Outer Harbor. This bench mark showed a sinking of .164 foot, while B. M. M97, less than 3000 feet east, on South Seaside Avenue, Terminal Island, San Pedro, showed an uplift of .052 foot. Tidal 8, a short distance to the southeast, is assumed, on the basis of its marigram, to have remained stable. Although the sinking of B. M. 38 could have been due wholly to compaction of the foundation of the viaduct, probabilities favor the interpretation that there was a bodily tilting of the earth's crust in this area.

B.M.'s Tidal 3 and Tidal 4, both at Inner Harbor, Mormon Island, one on a warehouse and the other on the pavement, showed sinkings of .237 and .236 foot, respectively. Within less than a mile in all directions except the northwest (where there was no neighboring station), the elevation change diminished to less than .050 foot or became positive. This sinking may have been connected with slumping into the

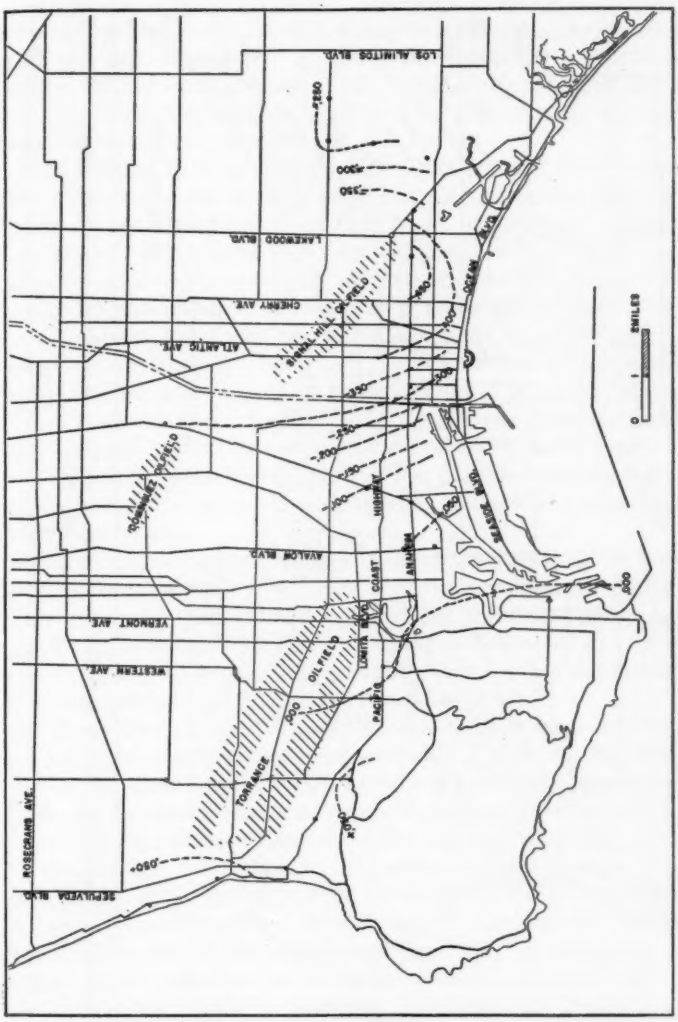


FIGURE 1.—*Elevation changes in the Long Beach area shown by leveling by the U. S. Coast and Geodetic Survey*

Adjustments of 1928 and 1931–1932. Bench marks used in both adjustments indicated by dots. Isobases (interval .05 foot) drawn by Gilluly and Grant. *Note:* the adjustment of 1928 treated original data taken over a period of 21 years (1906–1927) and hence is not homogeneous. This adjustment has been referred to an elevation of 11.129 feet for Tidal 8 Bench Mark, San Pedro, which appears, from marigrams, to have remained essentially stable.

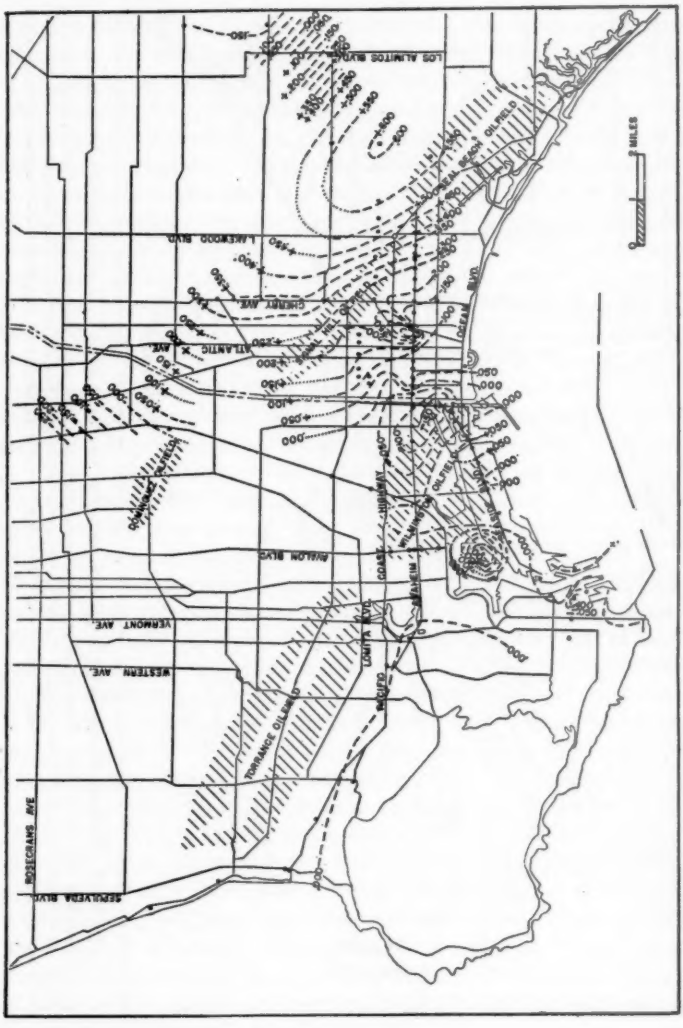


FIGURE 2.—*Elevation changes in the Long Beach area shown by leveling by the U. S. Coast and Geodetic Survey in 1931–1932 and 1933–1934*

The Long Beach earthquake of March 10, 1933, occurred in the interval between these surveys. Bench marks used in both surveys indicated by dots. Isobases (interval .05 foot) by Gilluly and Grant.

dredged channel of Inner Harbor, during the earthquake, though no supporting evidence is known.

The changes in elevation of bench marks along Terminal Island between the west city limits of Long Beach and the Los Angeles River appear to be unsystematic, with uplift and depression rather irregularly distributed. It is not likely that these changes, none of which attained .1 foot in magnitude, are significant of other than local movements, due either to lurching of the ground during the earthquake or to soil slumping from the same cause.

B. M. 283 (L.B.H.D.) and near-by B.M. 305 (L.B.H.D.), both near the Los Angeles Flood Control Channel, about 700 feet south of the west end of the Seventh Street Bridge, showed sinkings of .164 and .211 foot, respectively. Although B. M. 305 is on the rock wall along the flood control channel and might therefore be thought to have slumped somewhat during the earthquake, B. M. 283 seems not to be in a comparably unstable position. All the near-by bench marks except B. M. 338 (which shows an uplift of .043 foot) also show depression during the interval between the surveys. Accordingly it is likely that this depression is a result of crustal warping during the deformation of which the earthquake was a part. The sunken area, which extends northwest across Anaheim Street, is part way down the northeast flank of the Wilmington oil field structure and does not extend to the syncline between this structure and the Signal Hill anticline. Thus, if this movement is indeed tectonic, as we believe, it did not act in the same direction as the crustal movements of Pliocene and Pleistocene time.

B. M. 11, at the corner of California Avenue and Anaheim Street, showed an ostensible uplift between the two surveys of .423 foot, much greater than the uplift shown by the near-by bench marks both east and west. If this reading is not in error[2], it is possible that the discrepancy between the amounts of uplift here and near by is due to local lurching of the ground, though the possibility that it is due to local crustal uplift, perhaps along a fault, cannot be excluded.

REGIONAL CHANGES: North and east from the intersection of Daisy Avenue and Anaheim Street, except for the abrupt anomaly of B. M. 11, the elevation changes shown by the releveling of 1933–1934 form a remarkably regular system. Uplift is regular and increases toward a maximum of .610 foot at B. M. H51, on Palo Verde Avenue and Stearns Street (extended), and from this point decreases regularly toward the northeast and northwest. The area affected by this relative uplift is many square miles, and the regularity of the variation compels the interpretation that this is a result of crustal warping. It is noteworthy that the axis of maximum uplift lies northeast of that of the Long Beach (Signal Hill) oil field and is nearly 2 miles northeast of the postulated position of the Newport-Inglewood fault.

Elevation changes shown by the surveys of 1933–1934 and 1941.—In contrast with the changes shown by the surveys of 1931–1932 and 1933–1934, which revealed several purely local changes in elevation of the bench marks recorded, the resurvey of 1941 shows widespread and systematic changes with only minor deviations from regularity. Figure 3 shows the locations of the bench marks, the altitudes of which

[2] Highway surveys available to us, though less precise, show no consistent displacement of this bench mark, and it is at least possible that the great apparent displacement is due to an error in reading, despite the care exercised to avoid this in precise work.

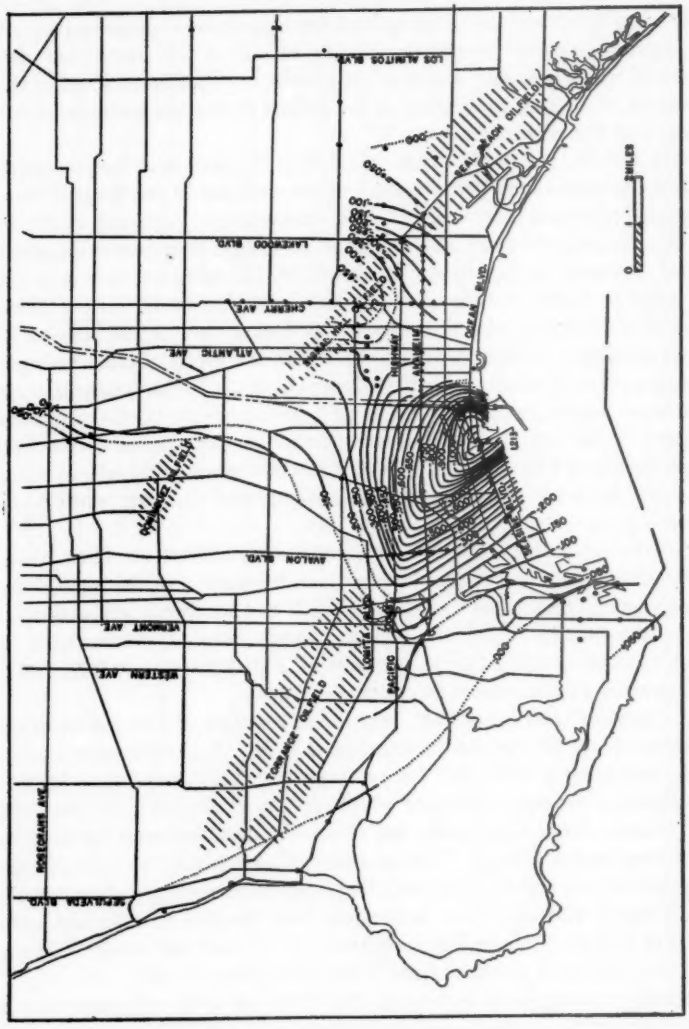


FIGURE 3.—*Elevation changes in the Long Beach area shown by leveling by the U. S. Coast and Geodetic Survey during 1933–1934 and June–July 1941*

Isobases (interval .05 foot) by Gilluly and Grant from level data at bench marks indicated by dots

were determined in both these surveys, and again, using the differences in elevation indicated, isobases of .050 foot intervals have been drawn.

This map shows that subsidence has occurred throughout the area northeast of the line of no change (zero isobase) which passes through Tidal 8, G 52 (San Pedro), and a point between Walteria and Redondo Beach. The only exception to this general subsidence is shown by B. M. H51, on Palo Verde Avenue and Stearns Street extended, which shows, according to the Coast Survey adjustment, no change in elevation. This is one of the bench marks held fixed in elevation during that adjustment, and accordingly its true change in elevation may not actually have been zero. To a geologist it appears strange that the bench mark that showed the maximum movement at the time of the earthquake should have been assumed stable during this adjustment.

There are two maxima in the field of general subsidence: one at B. M. 220 (near the southeast corner of the easternmost building of the Southern California Edison Company plant) which showed a subsidence of 1.213 feet between the two surveys, and one at B. M. B98 at the intersection of Burnett Street and Cherry Avenue, on Signal Hill, with a subsidence of .472 foot. The isobases, which were drawn mechanically and without consideration of geologic features, show a remarkable parallelism with the limits of the Wilmington oil field, as outlined in 1941. The depression centering on Signal Hill, where the isobases were drawn in a similar mechanical manner, does not show such notable parallelism. However, other survey data from the City Engineer of Long Beach show that, when more bench marks were surveyed in this area, there was a coincidence between the axis of maximum subsidence and that of the productive oil field, at least for the years 1925–1930 (Grant, 1944, p. 148–149).

We believe it highly significant that there is practically no similarity in pattern or trend between the isobases of Figure 2 and those of Figure 3, in the Harbor area. Figure 2 shows changes within a 2- or 3-year period during which violent tectonic activity took place; Figure 3 portrays the changes over a 7- or 8-year period in which no comparable earthquakes occurred, though the possibility of tectonic movement is not thereby denied. The Torrance earthquake of November 14, 1941, took place 5 months after the 1941 survey was completed.

Elevation changes shown by the surveys of 1941 and 1945.—The provisional elevations resulting from the resurvey of 1945 have been compared with the elevations resulting from the 1941 surveys, and the results are shown in the isobase map (Fig. 4). This map shows that the area as a whole has undergone a continued slight subsidence, with the area of most pronounced depression during the interval considered centered over the Wilmington oil field (hachured outline of Figure 2). It is quite strongly indicated that the area of maximum subsidence is nearly coincident with the junction of the Entrance Channel with Cerritos Channel, Channel No. 2, and Channel No. 3.

Elevation changes shown by the survey of March 1946.—During March 1946, the Coast Survey, under direction of Commander Lukens, releveled the line along Seaside Boulevard, tying, as usual, to the bench mark (Tidal 8) in San Pedro, whose level appears to be stable, to judge from the marigram of the near-by tide gauge on Pier 60, Los Angeles Outer Harbor. This survey was confined to a single line across the area of interest and accordingly gives no clue to the areal distribution of the subsidence. However, the consistency in pattern of subsidence since 1936 of all the

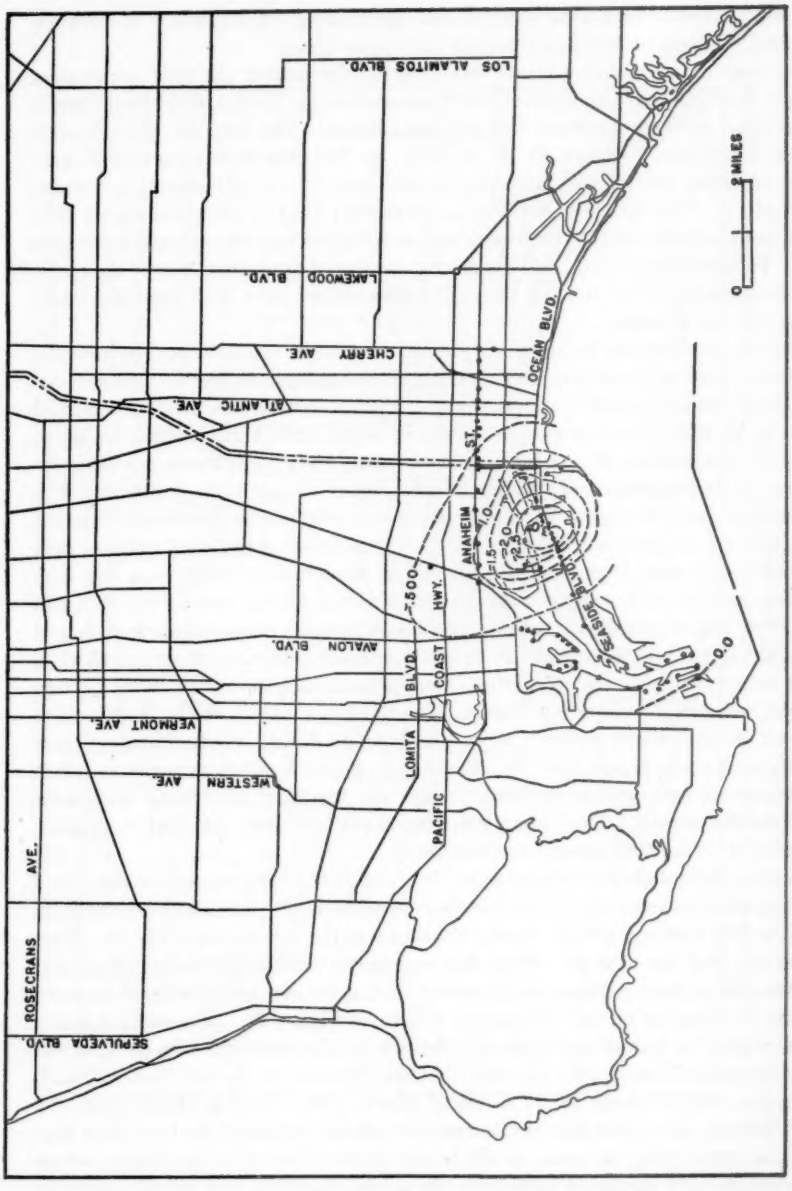


FIGURE 4.—*Elevation changes in the Long Beach area shown by leveling by the U. S. Coast and Geodetic Survey in 1941 and 1945*

Isobases (interval .05 foot) by Gilluly and Grant, based on comparisons of levels at bench marks shown by dots

several surveys by the Coast Survey and other agencies warrants the use of this single line as a basis for provisional isobases. Except along Seaside Boulevard the isobases of Figure 5 are controlled only by the pattern of preceding maps. Nevertheless,

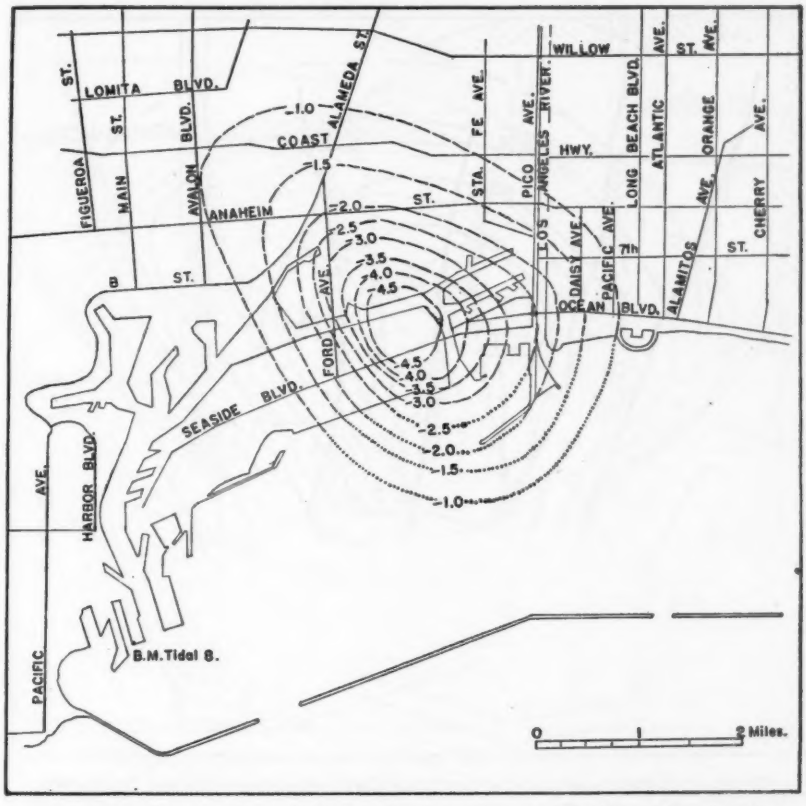


FIGURE 5.—*Elevation changes in the Long Beach area between 1933–1934 and March 1946*

As extrapolated from the data of Figures 3 and 4, supplemented by a single line of precise levels along Seaside Boulevard by the U. S. Coast and Geodetic Survey in March 1946. Isobases (interval .050 foot) by Gilluly and Grant.

utilizing the most recent accurate data, we believe it worth while to incorporate the map resulting from this extrapolation, which, with the qualification noted, summarizes all the changes from 1933–1934 to March 1946.

LONG BEACH HARBOR DEPARTMENT SURVEYS

Figure 6, reproduced from one drawn under the direction of Mr. C. L. Vickers of Long Beach Harbor Department, shows the total subsidence in the harbor area from 1937 to January 1, 1945. The original survey data have not been made available to us and are presumably irregular as to time. Mr. Vickers believes, on grounds that seem to us sound, that the subsidence in this area prior to 1937 was negligible as

Isobases (interval .05 foot) by Gilluly and Grant, based on comparisons of levels at bench marks shown by dots

compared with that subsequent to that year. The basis for this is the regularity of the marigram of the tide gauge at Berth 28, Pier D, Long Beach Outer Harbor, prior to 1937, and its parallelism with that of the gauge at Berth 60, Los Angeles Outer

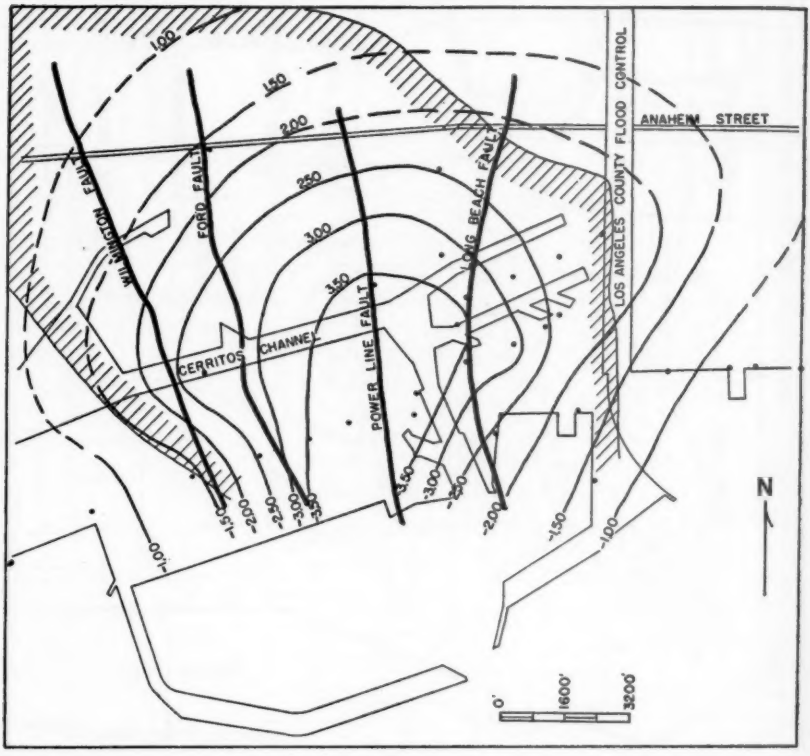


FIGURE 6.—*Elevation changes in the Long Beach Harbor area between 1924 and Jan. 1, 1945*

As deduced by C. L. Vickers and Roy H. Baldridge, Engineering Office, Long Beach Harbor Department, from surveys by the U. S. Coast and Geodetic Survey, Long Beach Harbor Department, and the City of Long Beach. Isobase interval 50 foot. Wilmington oil field boundary shown by diagonal lines.

Harbor (Fig. 10). Accordingly, Mr. Vickers has used survey data prior to 1937 without regard to year of survey as the starting elevation for each of the bench marks shown, and compared these elevations with those obtained in January 1945. The surveyed differences are recorded only to hundredths of a foot and because of the different dates of the original surveys the isobase map resulting from the surveys is not quite comparable with those of Figures 3 and 4. We are reproducing the isobase map exactly as drawn by Messers. Vickers and Baldridge because we thereby present a wholly disinterested interpretation by non-geologists of the elevation changes that have occurred here. The parallelism between the isobase of 1.50 feet

and the outline of the productive area of the Wilmington oil field is striking. With the same basic data and a bias toward a geologic control for the subsidence, it is

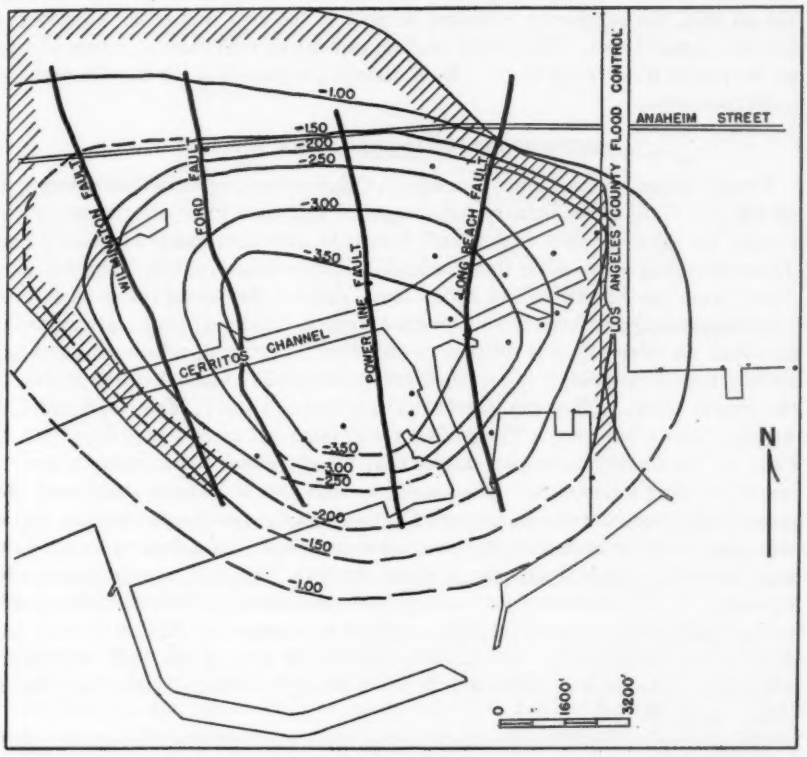


FIGURE 7.—*Elevation changes in the Long Beach Harbor area, 1924 to 1945*

As interpreted from the same survey data used by Vickers and Baldridge (Fig. 6) but with a bias toward geological factors having guided the course of the isobases. Drawn by Gilluly and Grant. Wilmington oil field boundary shown by diagonal lines.

possible, consistently with the data, to draw an isobase map even more strikingly parallel with the oil-field structure (Fig. 7).

SURVEYS BY THE LONG BEACH CITY ENGINEER'S OFFICE

The Office of the City Engineer compiled comparisons of levels run in 1934 with those run in 1940 on a series of graphs (Drawing No. B966, 6 parts, dated June 18, 1941). These graphs (not here reproduced) show changes in elevations of bench marks along Seaside and Ocean boulevards, Anaheim Street, Pico Avenue, Atlantic Avenue, and Cherry Avenue. These surveys indicate that every bench mark in this area subsided, as compared with the reference bench mark, Tidal 8, at San Pedro.

The amount of subsidence ranged from a minimum of .14 foot at Anaheim Street and Hathaway Avenue, to .77 foot at Water Street and Ocean Boulevard, the maximum subsidence shown. Except for greater subsidence in the few stations in the Wilmington oil field, the subsidence indicated in most of the area was rather consistently between .2 and .4 foot. These data conform rather well with those of Figure 3 based on the precise levels of the U. S. C. G. S., though the periods of the surveys were not quite coincident.

SURVEYS BY THE LOS ANGELES COUNTY SURVEYOR

Profiles drawn by the County Surveyor's Office comparing elevations determined by the U. S. C. G. S. Preliminary Adjustment of 1928 with those determined by the County Surveyor between March and June 1933 have been made available to us. These elevations follow a line from Redondo to Bixby School, chiefly along Anaheim Street; from Los Angeles to San Pedro; from Alamitos Bay along the shore to Pine Avenue; along Cherry Avenue from Ocean Avenue to Anaheim Street. Owing to the fact that the releveling was referred to the 1928 Adjustment, whose weakness has already been mentioned, it is not considered worth while to include these profiles in the present report. They can be referred to as Sheets 1 and 2, Map No. B 913, Los Angeles County Surveyor. The profiles are undated but carry a note dated Jan. 8, 1936, by the County Surveyor, stating that the elevations shown were subject to correction after adjustment. They confirm, with the limitations mentioned, the general subsidence of the area between Florence and the Los Angeles Harbor during this interval, in amounts ranging from a few hundredths of a foot up to .47 foot, together with a general subsidence along Anaheim Street of closely comparable amount, with the maximum just east of Atlantic Avenue (.393 foot). The profile along Anaheim Street passes through a point of no change near Ximino Avenue, and from there eastward there was elevation above the level of the 1928 adjustment amounting to as much as .233 foot at B. M. H 51, at Palo Verde Avenue and Stearns Street extended.

This survey confirms the elevation changes determined by the surveys of 1931–1932 and 1933–1934 of the U.S.C.G.S. (Fig. 2). The profiles between Pine Avenue and Alamitos Bay and that along Cherry Avenue also show subsidence amounting to a few tenths of a foot at most stations. Some of these figures are not consistent in detail, however, with those of crossing profiles, so that the reliability of the surveys, or at least of their adjustments, is not comparable to that of the U.S.C.G.S. releveling.

SURVEYS BY THE U. S. NAVY

Owing to the subsidence in the area of U. S. Navy Graving Dock No. 1, both during its construction in 1941 and later, the Navy has run a series of level lines from B. M. K-97, at the north side of Reeves field, to the Graving Dock, west of the entrance channel to Long Beach Inner Barbor. Inasmuch as the Coast Survey's levels showed that B. M. K-97 had already subsided .138 foot between 1933–1934 and 1941, and there is compelling evidence that it has continued to subside in the last 4 years, these surveys cannot be directly compared with others available to us. They do, however,

show a differential subsidence between Reeves field and the Graving Dock during the period November 1943 to October 1944 of .462 foot. The graph of the Navy data is reproduced here as Figure 8.

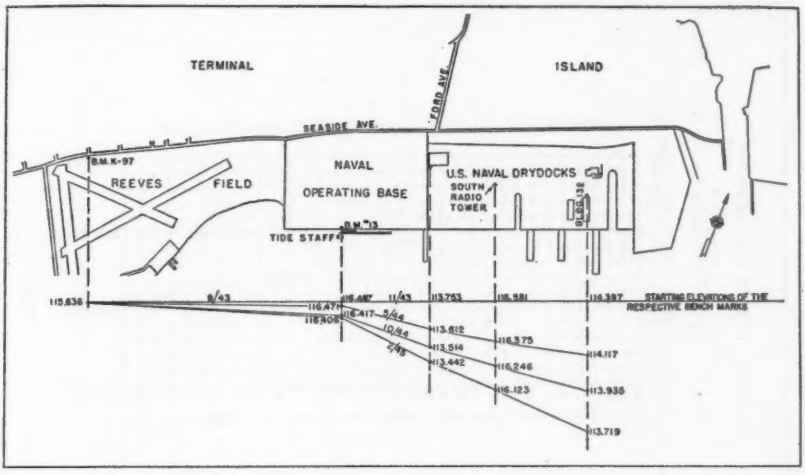


FIGURE 8.—*Sketch showing location of bench marks in the Naval Drydock area of Terminal Island, together with the changes in their elevations as referred to B. M. K-97, at Reeves Field*

From surveys by the Civil Engineer Corps, U. S. Navy. (Other surveys, as shown in Figure 4, indicate that B. M. K-97 was itself subsiding during the period of these surveys.)

Surveys by the Navy of elevations of the bench mark north of Building 132, about 700 feet west of the middle of the Graving Dock, show subsidence of .716 foot between November 1943 and March 1945, as referred to B. M. K-97 at Reeves field. This is at the rate of 0.54 foot per year. The survey dates and elevations (Fig. 9) show that the differential subsidence with respect to B. M. K-97 (which was itself subsiding during this time) went on at a nearly uniform rate during the period covered by the five surveys shown.

SURVEYS BY LOS ANGELES COUNTY SANITATION DISTRICTS

The Los Angeles County Sanitation Districts have run levels at several times between the Joint Disposal Plant, near the intersection of Lomita Boulevard and Figueroa Street, and the outfall of the disposal tunnel at Whites Point. The first survey was run in 1925 and was not so precise as the later levels, though its closure was small. Surveys in 1929, 1934, 1937, 1939, and 1942 were of high quality. The changes in elevation of the bench marks along their line have been discussed in detail in a report dated March 15, 1943, addressed to Mr. A. M. Rawn, Chief Engineer, by Fred D. Bowlus, Resident Engineer. These surveys show the subsidence of the Joint Disposal Plant during the 17-year period between the 1925 and 1942 surveys to have been .465 foot, as compared to a bench mark at San Pedro City Hall which

has been quite stable with respect to Tidal 8 B. M. Most of this subsidence has occurred north of Anaheim Street. At the Joint Disposal Plant the average rate of subsidence has been about .027 foot per year, or at the rate of 2.7 feet per century.

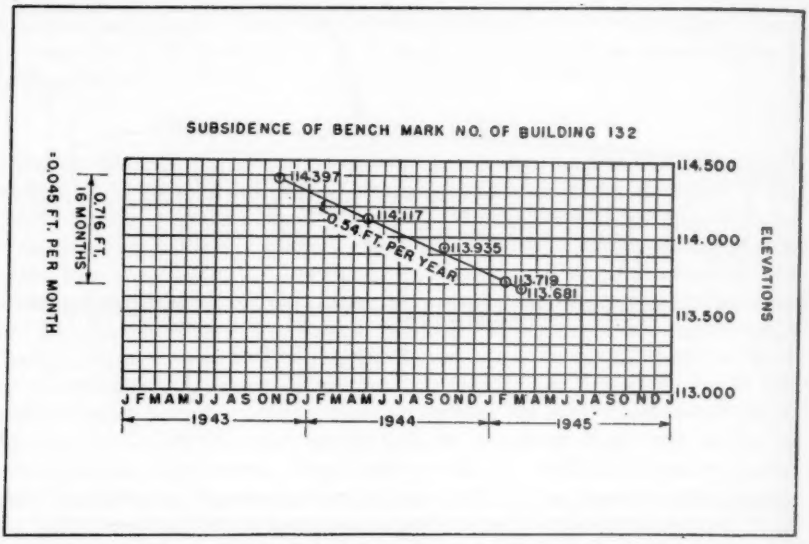


FIGURE 9.—*Graph showing rate of subsidence between November 1943 and March 1945 of a bench mark north of Building 132, Naval Drydock area (shown on Fig. 8) as compared to B. M. K-97, at Reeves Field*

Modified from graph by Civil Engineer Corps, U. S. Navy, from data shown on Figure 8

Mr. Bowlus points out that the rapid subsidence between 1925 and 1929 of nearly .05 foot per year coincided with heavy oil withdrawals in the near-by Torrance field and that the comparable rate of subsidence between 1939 and 1942 coincided with heavy withdrawals in the Wilmington field. Lateral migration of oil may thus have accounted for part of the subsidence, in the opinion of Mr. Bowlus, but, on the other hand, he concedes it may all have resulted from tectonic forces.

TIDE GAUGE COMPARISONS

Intercomparisons of tide-gauge records of various stations in the harbor area with the tide-gauge record at Berth 60, Los Angeles Outer Harbor, whose essential stability is well established, support the precise level data in showing the subsidence.

Figure 10 represents the marigram of the tide gauge at Long Beach Outer Harbor, Berth 28, Pier D. It shows essential stability with reference to the standard tide gauge at Los Angeles Outer Harbor, Pier 60, up to 1937. Since then it has subsided, with slight reversals, until, in January 1945, a difference of 2.75 feet was reached. It is probable that the sporadic reversals are due to meteorological conditions and do not reflect any actual relative uplifts of the Long Beach gauge. The long-term subsidence since 1937 is, however, real.

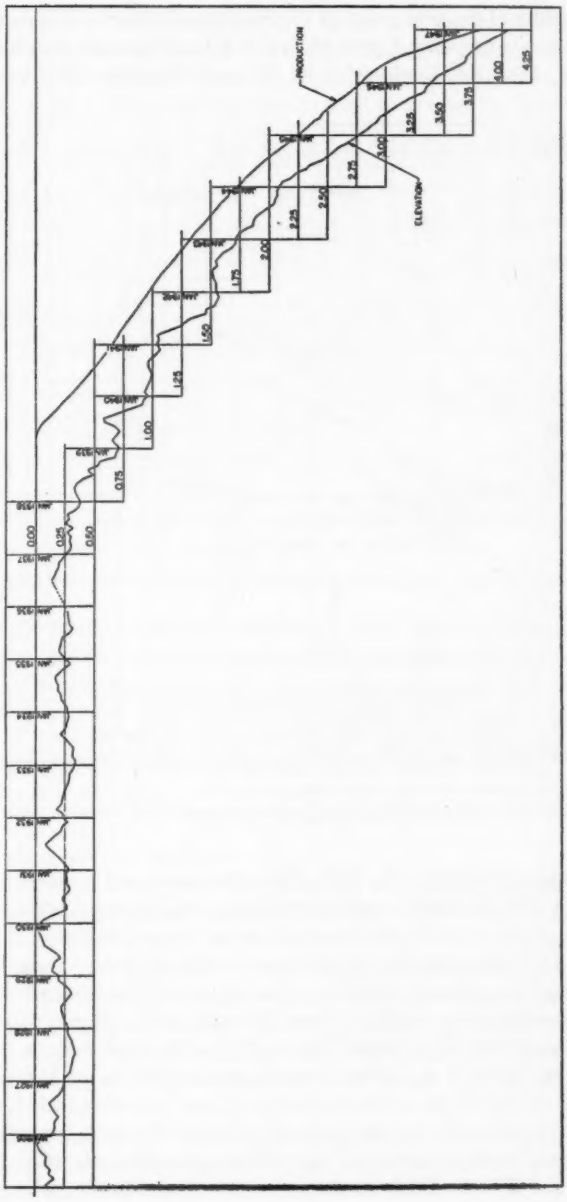


FIGURE 10.—*Marigram of tide gauge of Long Beach Outer Harbor, compared with that of Los Angeles Outer Harbor, 1925–1946*

Three months moving average. The line labelled "production" is in arbitrary units of oil produced from the lease nearest the tide gauge. Modified from graph by R. H. Baldridge, Engineering Division, Long Beach Harbor Department.

Similar comparison of the tide gauge at the Southern California Edison Company cooling-water intake is shown in Figure 11, which is based on data supplied by Mr. W. L. Chadwick, Manager, Engineering Department, Southern California Edison

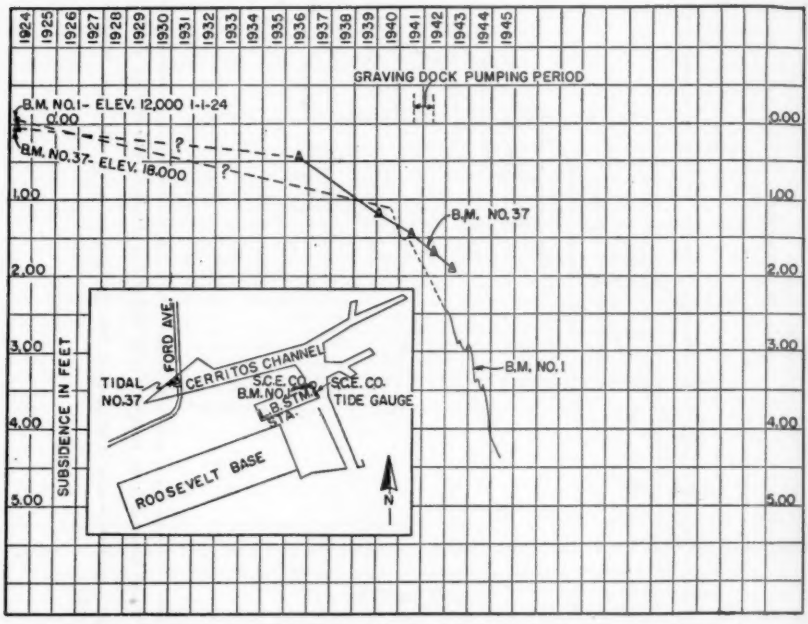


FIGURE 11.—*Subsidence of water-intake at Southern California Edison Company Steam Plant*

Based on levels and tide-gauge records of the company between 1924 and 1945; subsidence of B. M. 37, on the NE. wing of the Ford Avenue Bridge, based upon precise levels at various times between 1924 and 1943 by the Southern California Edison Company.

Company, in a letter dated May 21, 1945. This marigram, and precise levels taken at the site in early 1941, indicates a total subsidence from January 1, 1924, to March 1945 of 4.40 feet, of which 3.30 feet occurred after the summer of 1940. The rate of subsidence shown by this marigram during 1944 and early 1945 was greater than the overall rate between the summer of 1941 and the spring of 1943, which included the period of heavy pumping from the U. S. Navy Graving Dock. Figure 11 also shows the elevation changes at bench mark Tidal #37, on the Ford Avenue Bridge, as determined by precise levels at various times, also supplied us by Mr. Chadwick. This graph shows an essentially uniform subsidence rate, beginning early in the summer of 1936. Two comments may be made on this: (1) The subsidence had begun prior to any intensive development of the Wilmington oil field, which began in December 1936; and (2) Practically no change in rate of subsidence can be attributed to the heavy pumping from shallow sand during construction of the Navy Graving Dock, between July 1941 and May 1942.

Figure 12 shows an intercomparison of the tide gauges at Pier 60, Los Angeles Outer Harbor, and the General Petroleum Company's gauge at the east entrance to the Ford Slip (Long Beach Berth No. 95). This gauge is within a few hundred yards of B. M. Tidal 37 and may therefore be used to extend the record of subsidence at

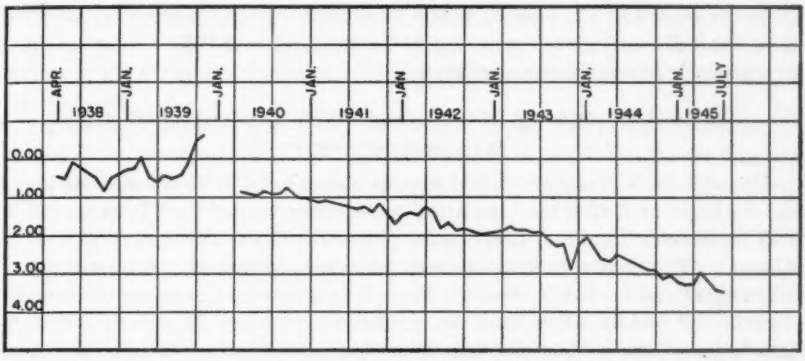


FIGURE 12.—*Subsidence of General Petroleum Corporation Tide Gauge at the east entrance, Ford Slip, Long Beach Inner Harbor, 1938–1945*

Based on comparison of 3-month moving averages with those of Berth 60, Los Angeles Outer Harbor

that bench mark, as shown in Figure 11, from 1943 to February 1945, within a reasonable approximation. Comparisons of the mean tidal levels by months shows this gauge to have subsided about 3.0 feet between January 1940 and February 1945. The highly irregular graph for 1939 can hardly reflect real changes in elevation of this gauge but must be due to local conditions, perhaps wind direction, water temperatures, temporary channel constrictions near it, or other factors.

SUMMARY OF ELEVATION CHANGES

Data cited serve to establish:

(1) Changes of elevation of the surface in the general area San Pedro-Compton-Alamitos Bay have been taking place practically continuously for more than 20 years.

(2) Except for an interval during which the Long Beach earthquake occurred, the entire area has undergone a net subsidence of a few tenths of a foot.

(3) The movements in the interval between the two surveys (1931–1932 and 1933–1934) which bracketed the Long Beach earthquake were irregular in the western part of the area, involving both uplift and depression; a broad surface doming centering nearly east of Signal Hill dominated the movement at this time in the eastern part of the area.

(4) Superposed on the broad regional subsidence are two areas of more localized and more pronounced depression. These center respectively in the Signal Hill and Wilmington oil fields.

(5) The differential subsidence centering at Signal Hill first became demonstrable between 1925 and 1930 because precise levels for earlier years are not available. The

"dimple" of roughly .4 foot depth was uplifted as a part of the broader doming in this area at about the time of the earthquake. Between 1934 and 1941 the scant data available show renewed differential subsidence here but do not suffice to outline the area of this subsidence in detail.

(6) The differential subsidence centering in the Wilmington oil field was trivial, if indeed it existed at all, prior to 1934. Subsidence possibly began soon after that date, but it did not become noteworthy before the summer of 1937. It has continued at a generally increasing rate since then.

GEOLOGY OF THE WILMINGTON OIL FIELD AND ADJACENT AREAS

PRELIMINARY STATEMENT

Although the Wilmington oil field was discovered in 1932, its actual development did not begin until after the completion in December 1936 of the "Terminal No. 1" well by General Petroleum Corporation, just north of the western end of Cerritos Channel. The field now extends from the neighborhood of the intersection of Wilmington and Lomita boulevards, where it is believed to be separated from the Torrance oil field by a structural sag, southeastward to and beyond the end of the Los Angeles County Flood Control Channel, a distance of approximately 5 miles. The maximum width of the field is more than 2 miles. Although there is no surface evidence of underlying structural conditions, a wealth of subsurface information has become available as the field has been developed. Among the more recent reports dealing with conditions in the field, those of Winterburn (1940; 1943), Crown (1942), the Wilmington Field Engineering Committee (1942), and Poland, Piper *et al.* (1945) have been drawn upon in the preparation of this summary.

STRATIGRAPHY AND STRUCTURE

General conditions.—The sedimentary rocks at Wilmington range in age from Quaternary to Miocene. Their total estimated thickness varies from 5700 to 7000 or

Age	Formation	Thickness	Lithology and remarks
		feet	
Recent Pleistocene	Unnamed San Pedro	1000 ±	Fresh-water sands, gravels, and clays
Pliocene	Upper Pico	800 ±	Alternating sands and siltstones
Pliocene	Middle Pico	0–200	Sands and siltstones
		Unconformity	
Pliocene	Repetto	875–1150	Gray and green shales, siltstones and sands at top, grading to interbedded grayish-brown shales and fine-grained sands toward bottom.
		Unconformity	
Miocene	Puente	4100 ±	Hard brown shales and sands; sands are fine and unconsolidated at top, becoming firmer and coarser-grained toward bottom. Top portion contains layers of laminated diatomaceous shale.
		Unconformity	
Jurassic?	Basement	—	Schist

more feet. They rest unconformably upon the irregular surface of an ancient schist body which is believed to be of Jurassic age. At a depth of approximately 2000 feet a marked angular unconformity separates the Middle Pico and locally the Upper Pico formation from the Repetto formation. Fresh-water aquifers within the area of the field appear to be confined to the San Pedro formation and overlying beds in the upper 1000 feet of these sediments, while the zones productive of oil lie between the unconformity and the basement schist. Winterburn (1943) has summarized the sequence, thickness, and character of the formations at Wilmington in the table on the preceding page.

Winterburn comments that very little coring has been done in the upper 2000 feet, so that the exact top of the Upper Pico and the areal extent of the Middle Pico have not been determined. His section, however, shows Upper Pico overlapping onto Repetto.

Developments to date in the Wilmington field indicate that accumulation of oil and gas has taken place on a wide, gently arched anticlinal structure, which plunges northwestward from an offshore point near the seaward end of the Los Angeles Flood Control Channel. It is believed that the structure extends eastward from this area as an offshore feature, but whether or not the northwestward plunge prevails farther in this direction is as yet unknown. Four main faults extend in a generally north-south direction across the anticline; from west to east, these are the "Wilmington", "Cerritos"[3], "Power Line", and "Long Beach Harbor" faults. They separate the field into structural blocks, which for convenience are numbered by the operators from I to V beginning on the west (Fig. 16). Detailed subsurface studies indicate several minor faults in the field, but these do not appear important in the present study. All of the major faults are normal, and all except the Power Line fault, which dips westward, dip 50°–60° eastward.

The four major faults are believed to act as impervious barriers, inasmuch as each of the five blocks recognized possesses its own characteristics as to gravity of oil produced, edgewater position, and pressures within producing zones.

Shallower strata.—The Upper Pico formation is about 800 feet thick. The lower part is dominantly sand and shale, and the upper 250 feet is silt and sandy silt (Poland, Piper, *et al.*, 1945, p. 144). It rests unconformably upon Middle Pico and overlaps onto the Repetto. The anticlinal axis in this formation lies about a mile northeast of that in the older rocks, so that throughout the Harbor district the Upper Pico is homoclinal, dipping southwestward. (*See* Figure 13, modified from Poland, Piper, *et al.*, 1945, Pl. 704B). As pointed out by Poland, though the Upper Pico contains essentially fresh water, at least inland from the coast, it has not yet been tapped by water wells, so that there has been no significant change in piezometric head in it within recent years.

Overlying the Upper Pico, with local unconformity, is the San Pedro formation. According to Poland (p. 144, 151, 153), this formation ranges from about 600 to about 1100 feet in thickness in the Harbor area. The lower 300 to 400 feet is largely sand and gravel, but in the area of Terminal Island and toward the east, between the Los Angeles River and Belmont Pier, in Long Beach, the sand and gravel lenses laterally

[3] Formerly the Ford fault was considered to separate Blocks II and III.

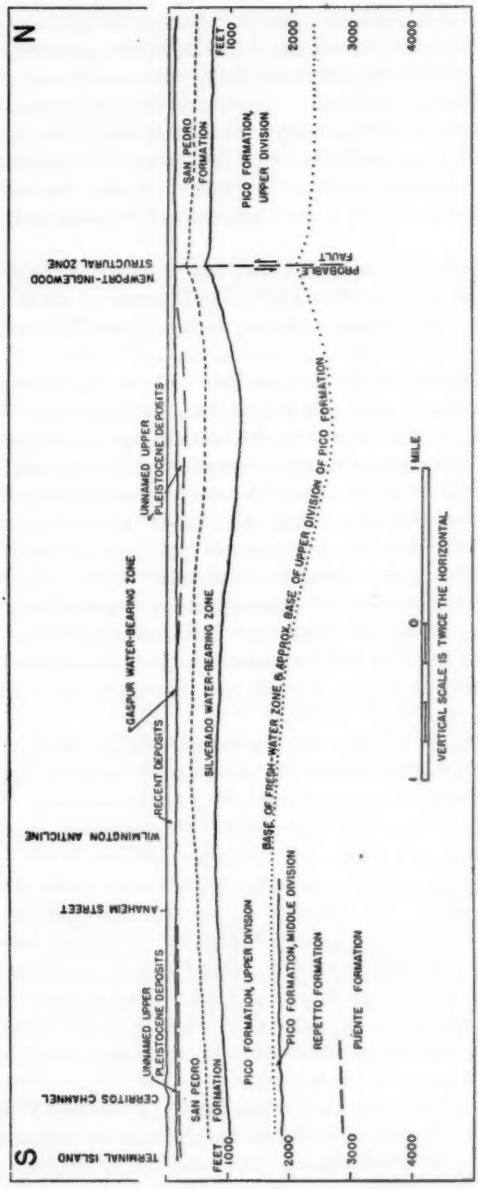


FIGURE 13.—*Generalized geologic section, Terminal Island toward Domingues Gap*

Modified from J. F. Poland and A. M. Piper, U. S. Geological Survey unpublished records

into finer silt, and the permeability of the formation decreases. The coarser part of this lower deposit is an important aquifer, referred to by Poland as the "Silverado water-bearing zone". The upper part of the San Pedro formation is finer-grained and less permeable to water. Overlying it locally are deposits of fine sand, silt, and clay that in places attain about 100 feet in thickness. These are referred to the Upper Pleistocene by Poland but are not given a separate formational name.

Poland has prepared a map, based on well records, showing the base of the San Pedro formation throughout the southern part of the Los Angeles Basin. This map shows that the San Pedro formation (the base of which is essentially identical with the base of the "Silverado water-bearing series") is folded into anticlines and synclines. The axis of the anticline in this formation near Wilmington lies northeast of the axis of the Wilmington anticline in the older petroliferous rocks. Poland's map shows that the Harbor district is underlain by a wedge-shaped mass of the San Pedro ranging from about 550 to 1000 feet in thickness. No particular features of this formation seem to correspond in distribution with the area of subsidence in the Long Beach district.

Overlying the San Pedro and the thin and discontinuous unnamed Upper Pleistocene beds is a thick gravel formation of geologically Recent (post-Pleistocene) age. This is the "Gaspur water-bearing zone" of Poland, Piper, *et al.* (1945, p. 97) and comprises a lower zone of clean gravel ranging from 25 to 60 feet in chickness, overlain by medium- to coarse-textured sand of similar range in thickness. The bottom of this zone is as much as 150 feet below sea level at the coast. Poland interprets this as the channel deposit of an ancestral San Gabriel River, formed at a time of lower sea level than the present. This zone is an important aquifer, and its outcrop on the floor of San Pedro Bay was the source of springs of fresh water, as can be deduced from the isopeistic map drawn by Mendenhall (1904, Pl. 4) and confirmed by George Bouton (Reagan, 1917, p. 54) who reported in 1915 that:

> "It has been the practice of fishermen at San Pedro when they arrived about a mile outside the beach, and about midway between Long Beach and San Pedro, to lower a jug weighted so it would sink and corked up so that when it reached a certain depth the pressure would push the cork in, and the jug would fill with pure, fresh water."

The upper part of the Recent deposits consists of finer material—silt, clay, and fine sand—deposited by streams and to some extent reworked by beach processes. It records either a rising sea level or a slight sinking of the land, but probably the former, as the deposit extends inland with a thickness of 60 to 75 feet in Dominguez Gap (Poland, 1945, p. 94), and the gradient is almost certainly no steeper at present than that upon which the material was deposited, and may actually be flatter.

The upper few feet of this deposit contains peat beds, deposited in salt marshes behind coastal barrier beaches or spits.

Oil zones.—Four productive oil zones had been developed at Wilmington prior to 1945. Beginning with the shallowest, these are briefly described as follows:

(1) Tar zone: At structurally high locations this zone, which is 250 to 400 feet thick, is encountered at about 2200 feet. Each well yields between 100 and 300 barrels of oil per day varying in gravity from 12° to 15° A.P.I. The zone is present in all 5 blocks, but is not everywhere productive, owing to the presence of water. Relatively unconsolidated sands constitute approximately 40 per cent of the zone.

(2) Ranger zone: The top of this zone, which ranges in thickness from 400 to 600 feet, lies at a depth of about 2300 feet in structurally high positions. The zone is productive throughout each of the 5 blocks, and yields ranging from 50 to 2700 barrels per day have been recorded. The oil varies in gravity between 12° and 25° A.P.I. Sand content is estimated as from 15 to 30 per cent.

(3) Terminal zone: This zone is 1000 or more feet thick and is from 50 to 70 per cent oil sand. It lies at a depth of about 2800 feet where structurally high and is productive in all fault blocks. The upper 400 feet of the zone yields oil varying in gravity from 14° to 25° while that in the lower part ranges from 26° to 31°. The zone has wells yielding from 100 to 8000 barrels per day.

(4) Ford zone: Developments in this zone to January 1945 had been practically confined to Blocks I and II. The top of the zone lies at a depth of about 4500 feet in structurally high positions on Block II, and the zone averages 750 feet in thickness, of which 25 to 35 per cent is oil sand. Production ranges from 100 to 900 barrels of oil of 28°–32° A.P.I. gravity per day. Ordinarily the degree of consolidation of oil sands increases with depth, but porosity and permeability are relatively high, except in the Ford zone.

Still another deep sand, the "237 Zone," has been recently discovered. It is not here considered as our quantitative data were gathered as of January 1945.

Despite the heavy withdrawals of oil from the Wilmington field, edgewater encroachment has been relatively slow except in the Terminal zone, where threatening water sands are interbedded with the oil sands. It has been suggested that in the Tar and Ranger zones a tarry condition at the oil-water interface has slowed down the rate of water encroachment.

Gas-oil ratios in the field were low to begin with, increased in all zones as field development progressed, and are now decreasing in certain depleted areas.

Longitudinal sections in the axial portion of the Wilmington field indicate thickening of oil sands in the Ranger and Ford zones toward the east and southeast, while those of the Terminal zone remain about the same thickness; the Tar zone sands show a remarkable thinning eastward from Block I.

The primary cause of loss of pressure in the oil measures in the Wilmington oil field has been the withdrawal of oil and gas without compensating ingress of water under hydrostatic head. There are two factors which have controlled pressure reduction: the amount of oil and gas withdrawn and the thickness of the oil- and gas-saturated sands. Owing to the difference in time of development and in the spacing of the wells, some areas where the sands are thin have produced as much or more oil than others with thick sands. With equal amounts of oil and gas withdrawn per acre, the greatest loss in pressure has been in areas of thinner sands.

In the Tar-Ranger and Terminal zones, development was deferred longest in the beach and offshore area of the southeast part of the oil field. The spacing of the wells here is wider, and the sands are relatively thicker than in the intensively drilled townlot areas immediately to the north and in the northwest end of the field. Consequently reduction in pressure has been generally less in this area, but has increased progressively to the north where development was earlier and the sands thinner.

Subsequent to January 1, 1945, two wells were completed in the Ford zone in the

east portion of the field. As these are probably separated from other Ford zone wells to the west by impervious faults, it is unlikely that any appreciable reduction in original pressure has yet taken place in this recently developed area. Reduction in pressures in the Ford zone has been moderate in Block II and adjacent portions of Block I, but is greater in the northwest (townlot) portion of Block I, where this zone has been more intensively developed.

Wissler (1943, Pl. 5) has supplied a correlation chart of the Los Angeles Basin oil fields which shows a general continuity of producing horizons between many of the fields. Thus, the Tar-Ranger and Terminal zones at Wilmington extend into and are wholly or in part productive at the near-by Dominguez and Long Beach (Signal Hill) fields; at Torrance, however, the Tar and Ranger zones are either absent or non-productive. The Ford zone is represented at Torrance by the Del Amo zone and at Long Beach by the De Soto zone.

The removal of oil and gas from such zones in the Wilmington and adjacent oil fields has evidently permitted movement of water in the zones from beneath the intervening, presumably synclinal, areas toward the fields. Although such movement is probably slow, it may in part account for the slight regional subsidence between the Torrance-Wilmington anticline and the Dominguez-Long Beach line of deformation.

FIELD DEVELOPMENT

Intensive development of the Wilmington field began in Blocks I and II adjacent to the General Petroleum discovery well west of the Ford property. The Ford land was rapidly drilled up as were adjacent portions of the Union Pacific holdings. Almost simultaneously, in 1936–1937, development of the townlot district north and northwest of the Ford-Union Pacific area began, and about a year later the Harbor area developments started. Crown (1942) reports that as of January 1, 1942, more than 140,200,000 barrels of oil had been produced from zones having a probable productive extent as follows: Tar zone—2000 acres, Ranger zone—4000 acres, Terminal zone—2800 acres, and Ford zone—1800 acres.

Total field production to January 1, 1945, amounted to approximately 245,000,000 barrels, according to a tabulation by the Long Beach Oil Development Company. The distribution of this yield among Blocks II, III, IV, and V is referred to elsewhere in this report.

Close spacing of wells characterizes the townlot area of the field and a portion of the Harbor District, but wider spacing prevails in portions of Blocks I and IV and in Blocks II and III, where property holdings are in larger tracts.

POSSIBLE CAUSES OF SUBSIDENCE

PRELIMINARY STATEMENT

We have presented the main features of the subsidence and the general geologic setting. Investigation of the cause of the subsidence requires evaluating the probable effectiveness of each mechanism that can be considered to have brought it about or contributed to it. These appear to be the following:

(1) Tectonic movements—*i.e.*, crustal warping and tilting brought about by deep-seated forces within the earth
   a. Direct uplift or depression of the surface
   b. Lurching and slumping of surficial materials due to earthquake shocks
(2) Changes in ground-water conditions
   a. Changes in pressure of confined water
   b. Changes in water-table conditions
(3) Compaction of sedimentary materials
   a. General secular compaction due to load
   b. Compaction of fill in areas of "made" land
(4) Changes in reservoir pressure due to oil operations
   a. Elastic compression of oil sands due to relief of internal hydrostatic pressure
   b. Compaction of oil sands due to rearrangement of grains under load
   c. Thinning of shale beds in association with oil sands because of loss of water into the oil sands with diminishing pressure in the sands

TECTONIC MOVEMENTS

Introduction.—Southern California is one of the most active regions of the world tectonically. The stratigraphic sequence indicates repeated submergence and elevation of local segments of the earth's crust at many times from the Pliocene to the present. There is of course historic record of many earthquakes, and changes of level associated with some of them have been notable. Accordingly, there is ground for assuming that any changes in elevation that have taken place in the area are prima facie to be attributed to crustal deformation.

The causes of tectonic movements are so obscure that it is always possible to assert their effectiveness without the possibility of direct disproof; in the nature of the case, the demonstrated adequacy of another mechanism known to be operative and competent to produce the observed effects can only make it unnecessary to appeal to the unknown tectonic forces. Nevertheless, there are common associations of tectonic features—"habits"—and it seems possible to evaluate the probability that a given surface movement is, or is not, of tectonic origin by ascertaining the degree to which the movement conforms to such common habits. With this objective, the geological history of the local area is considered in more detail in the following section.

Geological setting.—Within the Los Angeles Basin the Newport-Inglewood zone of faults and en echelon folds is apparently the locus of the most striking Recent crustal movements. This zone trends northwesterly, passing about 6 miles northeast of the Wilmington-Long Beach Harbor area in which the subsidence here considered has occurred. Any surface movements in an area so near this zone of known recent activity might naturally be attributed to tectonic activity along this zone.

The Newport-Inglewood zone has been described by many geologists (Eaton, 1923; 1924; 1926a; 1933; Ferguson and Willis, 1924; Jensen and Robertson, 1928; Reed and Hollister, 1936). They pointed out the linear disposition of many en echelon anticlines along this zone, the strong suggestion that the pre-Tertiary basement changes, along it, from schistose on the southwest to granitic on the northeast, that numerous earthquake epicenters occur along it, and that there are evidences of horizontal move-

ment on faults in this zone (Driver, 1938). Apparently all agree that this zone is of fundamental importance in the structure of the area. It is suggested that a major fault lies buried beneath the Tertiary cover and that right-hand strike-slip movement has taken place along it.

Seismological investigations confirm several elements of this hypothesis (Wood, 1933; Gutenberg, 1934a; 1941; Benioff, 1938). Wood and Gutenberg independently fixed the epicenter of the Long Beach earthquake of 1933 almost on the postulated fault near Newport. Benioff (1938) traced the progress of the actual displacement along the fault for 28 km, as far northwestward as the neighborhood of Signal Hill. Further, Gutenberg's (1941) study of first motions of southern California earthquakes permitted him to state that,

> "Southern California and central California from the oceanic margin of the shelf to beyond the regions of Owens Valley and Imperial Valley are under a shearing stress such that the tendency is directed approximately toward the southeast at the bottom of the continent relative to the crust beneath the Pacific."

It is reasonable to assume, in accordance with the "elastic rebound" theory, that stresses build up slowly, so that bending and horizontal and vertical movements occur along this zone during the intervals between earthquakes. We attribute the uplift centering east of Signal Hill (Fig. 2) to tectonic forces at the time of the Long Beach earthquake. Other areas may well be undergoing tectonic movements. There is considerable evidence for them elsewhere in the Los Angeles Basin, notably near Inglewood and Watts (Grant, 1944).

The pertinent geological features in the history of the Wilmington area appear to be: The upwarping of the Wilmington anticline took place in three, perhaps four, stages: (1) post-Repetto (lower Pliocene); (2) possibly post-Middle Pico (mid-Pliocene); (3) post-Upper Pico (late Pliocene); and (4) post-San Pedro (mid-Pleistocene). As far as is known, the axis of the fold remained fixed, geographically, during the first two episodes, but during the two later stages the maximum uplift appears to have taken place along an axis parallel to but about a mile north of the axis in the Miocene rocks. (*See* Figure 13.) The migration of the axis appears definite, though the synclinal axis to the north appears to have remained fixed.

Repeated uplift along essentially identical axes—"consequent folding"—is of course a common history of fold development. As with most geological generalizations, however, there are exceptions (the Coalinga area in California being an example). Thus, the coincidence of the present subsidence (which must be forming a syncline of small amplitude in the shallower strata) with the crest of the Wilmington anticline, though it raises a doubt as to the movement being tectonic, cannot be regarded as disproving such a cause.

Many anticlines have downfaulted segments along their axial regions, and the localization of the subsidence along the crest of the Wilmington anticline might suggest that it is due to the current development of such a graben. This possibility seems remote, however, for the following reasons:

(1) Available level data suggest no abrupt boundaries for the depressed area; the subsidence seems to die out gradually away from the center.

(2) Fault troughs in other anticlines appear to have been formed at the time of the

folding. Level data fail to suggest any current growth of the fold, and, indeed, the axis in the youngest beds involved in the anticline lies north of the depressed area (Fig. 13), so that a graben should be displaced to the north also, with respect to the anticline in the Repetto and older beds.

(3) Subsurface data for the field give no suggestion of an axial fault trough, even in the shallow zones, and thus there is no likelihood of modern rejuvenation of a more ancient group of faults.

(4) It is indeed more than doubtful whether axial grabens ever represent real depression of the central segment. Much more likely, the central segment merely lags behind the lateral segments during uplift of the fold (Woodring, Stewart, and Richards, 1940, p. 152–153). The subsidence here to be accounted for represents depression with respect to sea level and not merely with respect to the bordering segments.

The land forms of the coastal region of the Los Angeles Basin are largely constructional, in the physiographic sense. Except in the Palos Verdes Hills and the uplifts of the Newport-Inglewood zone, they are composed of river flood plains, beaches, and lagoonal marshes. Only along the hills do the land forms record subaerial erosion. These facts clearly indicate that the recent history of the land in this region has been one of subsidence.

Local stratigraphy indicates no record of uplift since the folding of the San Pedro formation in mid-Pleistocene time, though there is record of Recent folding in the Palos Verdes Hills a few miles to the west (Woodring, Bramlette, and Kew, 1946, p. 109). The Gaspur water-bearing gravel, the oldest of the Recent strata at Wilmington, shows no recognized folding. This coarse gravel, which could not have been formed below sea level, is now buried to depths of 75 feet as far inland as Dominguez Gap, more than 6 miles from the coast. This burial records a negative epeirogenic movement, due either to uniform subsidence of the land over an area of many square miles or to a rise of sea level (Poland, Piper, *et al.*, 1945, p. 94).

The superficial unconsolidated sediments of Terminal Island and in the neighborhood of the old channel of the Los Angeles River have been studied in another connection (Grant, 1939). Test holes to a depth of 14–18 feet were made on Terminal Island. These showed a peaty layer averaging less than 6 inches thick and characterized by remains of *Frankenia*, *Distichlis*, *Salicornia*, and *Spartina*. These plants do not grow below Lower Low Water, and *Spartina* has also a definite upper limit of about 5 feet above this datum. Two mollusks, *Cerithidea californica* and *Melampus olivaceous*, occur in the same sections and also have sharply defined limits with respect to sea level. The peat layer corresponds in distribution with tidal marshes as shown on old charts dating from 1859 for the northern part and 1888 for the southern. Dredging and filling did not destroy these marshes until about 1914. The deposits, in 1939, were found practically at sea level. They may have been depressed a few tenths of a foot below their position of growth but almost certainly were not uplifted. The peat layer was discontinuous north of Cerritos Channel so that little can be said of level changes there immediately prior to the Coast Survey's work. The test borings were made in 1939 when, according to the marigrams (Figs. 10–12), the local subsidence had been under way for about 2 years. Accordingly there is no suggestion

of any considerable subsidence of Terminal Island in the 75- or 80-year period prior to 1937.

Geological inferences from survey data.—Detailed analysis of the elevation changes recorded in Figures 1–7 shows two types of movement. At about the time of the Long Beach earthquake several areas were uplifted—the largest involving the formation of a low anticline whose axis (.61 foot uplift) was near Palo Verde Avenue and Stearns Street extended. Generally, however, successive surveys show a cumulative slow subsidence over a wide area, including that of the anticline just referred to. Since 1931 this general subsidence has amounted to .1–.4 foot. It seems probable that this is due to regional causes.

Superposed on this, however, is the marked localized subsidence—more than 4 feet greater than the average—centering in the Wilmington oil field—Long Beach Harbor area.

Elevation changes indicated by successive surveys in this general area were first noted by G. L. Nicholson, formerly Chief Harbor Engineer, Los Angeles Harbor Department (Nicholson, 1929). He pointed out that precise levels in Los Angeles Harbor indicated a general subsidence of most of the San Pedro area with respect to a datum on Rattlesnake Island. With reference to this datum, a bench mark on the Lower Reservation at Fort Mac Arthur and one on Terminal Island near its western end showed a slight uplift (.02 foot). Another near San Pedro City Hall showed essentially no change. The maximum subsidence in the field was .20 foot. On the basis of a sudden increase in subsidence north of an imaginary line, Nicholson projected a probable fault across the surveyed area. This postulated fault is an extension of one shown on Willis' and Wood's map (1922) as extending southeasterly from Redondo toward San Pedro along the north border of the Palos Verdes Hills.

Woodring, Bramlette, and Kew (1946, p. 110) mapped this zone in great detail and found no exposed fault, though they do not deny its existence as a feature of the basement. They record overturning of beds at depth as inferred from two well logs along this zone and point out that this has been a highly mobile belt since Pliocene time. The Gaffey anticline and Gaffey syncline (Woodring, 1946, p. 111) have been rejuvenated in Recent time. Their eastward extension into the Harbor area (they would project across western Terminal Island) has not been detected in the structure. There is some evidence of slight differential displacements between 1925 and 1938 of bench marks near Gaffey Street situated respectively on the north flank of the anticline (uplift .003–.007 foot) and south flank of the syncline (steady subsidence of a few hundredths of a foot) (Bowlus, 1943). Unfortunately no bench marks have been located on the axes of the folds, between which the largest differential movements would be expected. Nevertheless there is here a strong suggestion of probable, though slight, tectonic movement within the past 20 years just west of the area here considered. Similar movements are suggested farther west, at Walteria, where an uplift of .011 foot is indicated between 1928 and 1933, according to surveys by the Los Angeles County Surveyor.

Lurching, slumping, and landsliding.—During the passage of earthquake waves through and along the earth's crust sudden surficial displacements may occur. These are to be distinguished from slow crustal deformation involving rocks at depth.

Lurching refers to the shaking of more or less incoherent superficial sediments such as damp or saturated alluvial bottom lands as a result of the passage of surface earthquake waves. The inertia of incoherent alluvium prevents its partaking entirely of the high accelerations of the earth beneath, and thus it may be displaced, its new position being not necessarily more stable than its former one (Byerly, 1942, p. 67–68). In local alluvial basins a resonance effect may be produced, magnifying the displacements. The Long Beach earthquake of March 10, 1933, produced some conspicuous lurches in bottom lands. The horizontal displacements in the Alamitos Bay section of Long Beach, described briefly in another part of this report, probably were due to lurching during this earthquake. Vertical displacements may also accompany lurching. Surficial uplift may result from changes in the packing of sediments or subsidence from the squeezing out of water and decrease in porosity.

Slumping or down-hill creep may also be promoted by surface earthquakes waves. When the displacement becomes significant it is probable that it would be recognized as a landslide.

Very probably many of the small displacements indicated on Figure 2 are due to minor lurching and slumping. The irregular distribution, both in sign and amount of movement, between the surveys of 1931–1932 and 1933–1934 strongly suggests local differences in the response of the surficial material to the strong ground waves at the time of the Long Beach earthquake.

The extremely low relief of the area, the gentle slope of the sea floor, the absence of good gliding horizons at reasonable depth, and the fact that the isobases close smoothly all around the depressed area argue against landsliding as the cause of the main subsidence. The dredged material added to Terminal Island constitutes a slight additional local load, but much of it came from the inner harbor. The dredging from the outer harbor does not seriously oversteepen the seaward slope, and there is no suggestion in the areal pattern of the subsidence of a tilting such as is usual in landslide blocks. Furthermore, most of the dredgings on Terminal Island were placed on the seaward side, whereas the greater depression has occurred on the landward side.

Horizontal movements.—Horizontal movements of triangulation stations and changes in length of precisely measured lines have occurred in the Long Beach Harbor area, but up to 1945, when the first phase of our study was completed, such movements were small. Surveys before and after the Long Beach earthquake of 1933 showed notable horizontal movements in the Alamitos Bay area, east of Long Beach, but these were probably caused by lurching of water-soaked sediments traversed by surface waves. Some horizontal movements at and near the Newport-Inglewood fault are probably truly tectonic.[4]

Tilting due to differential subsidence.—Tsuboi (1939) has summarized the Japanese attempts to detect forthcoming earthquakes from ground-tilt readings. In 1942 the Long Beach Harbor Department installed a Merritt Tiltmeter, provided by the U. S. Coast and Geodetic Survey, in Recreation Park about a mile southeast of Signal Hill.

[4] After this paper was completed and submitted for publication we learned of notable horizontal movements in the area of subsidence (Data from Los Angeles County Surveyor and Engineer). These appear to represent centripetal movements of triangulation stations in the area of subsidence, and thus are apparently related to the subsidence. Data are not yet available for adequate discussion of these movements (some lines shortened as much as 2 feet), but, insofar as known, they do not suggest tectonic factors.

The records of this machine, according to Mr. F. P. Ulrich of the Coast Survey, are so confused because of deflections obviously related to periods of rainfall and by abundant microseisms that no interpretation of crustal movement is yet possible. This tiltmeter is close to the Newport-Inglewood zone and several miles from the area of maximum subsidence.

Within the area of marked subsidence, the tilting is only indirectly determinable from precise level data. The most marked tilting so detected has been found in the Southern California Edison Company property, along Seaside Boulevard just north of the Navy Yard and along Water Street, about 2 blocks west of Pico Street.[5]

Leveling by the Edison Company showed that differential vertical movement between the southeast and southwest corners of their Plant 3 building between June 2, 1941, and January 20, 1943, amounted to 0.07 foot in 237 feet. By April 1, 1943, this differential subsidence had diminished to 0.029 foot and by December 14, 1944 to only 0.023 foot. A possible interpretation of these records is that the subsidence is spreading laterally from a "sink" near the center of the isobases.

The other two localities fail to supply evidence of similar reversal in sign of differential vertical movements. The maximum tilt recorded along Seaside Boulevard amounted to about 0.075 foot per 100 feet between 1937 and 1944, an angular displacement of about 2½ minutes, eastward. On Water Street the tilt was westward at 0.075 foot per 100. These data are from the Long Beach Harbor Department.

Summary.—In view of all these evidences of recent movements of more or less well-established tectonic origin in the general area of which this is a part, it is obviously reasonable to attribute the rapid subsidence in the Long Beach area to the same tectonic causes. This is nevertheless unlikely, we believe, for the following reasons:

(1) The local amplitude is a whole order of magnitude larger than the average of the supposed tectonic movements.

(2) Available data indicate that the area affected coincides almost precisely with the productive area of the Wilmington oil field.

(3) The movement is precisely opposite to that expected in rejuvenated folds, and its areal pattern does not conform to that of an axial graben.

(4) The movement conforms qualitatively (and we believe we show later, quantitatively) with what might be expected to be the response of oil sands to pressure reduction within them brought about by oil-field exploitation.

(5) So far as may be judged from marigrams, the excessive subsidence began shortly after the beginning of considerable oil production.

(6) The much smaller localized subsidence at the time of construction of the U. S. Navy Graving Dock, in 1941, has been shown to have been caused by the response of shallow aquifers to dewatering. Further, part of this small localized subsidence rebounded promptly, when pumping at the dock ceased, and was therefore partly elastic. Accordingly it is reasonable to believe that qualitatively similar effects might occur in the oil sands.

(7) Other oil fields with sandstone reservoirs show similarly concentrated surface

[5] After this paper was submitted for publication leveling surveys indicated a maximum tilt of the land due to subsidence of 0°5'11" near Seaside Boulevard and Twenty fourth Avenue, on Terminal Avenue. This was in 1947 when the maximum amount of subsidence had reached over 7 feet.

subsidence, though not often of such large amount (Santa Fe Springs, Long Beach, Playa del Rey, and Huntington Beach, California; Goose Creek, Texas; and Lake Maracaibo).

EFFECTS OF CHANGES IN GROUND-WATER REGIMEN

Introduction.—The marked subsidence in the Santa Clara Valley, which between 1912 and 1937 amounted to as much as 5.57 feet, has been attributed to extraction of ground water and the concomitant dewatering and shrinkage of clays in contact with the aquifers (Tolman and Poland, 1940). Subsidence on a much smaller scale took place on Terminal Island during the construction of the U. S. Navy Graving Dock in 1941 and was also definitely associated with lowering of pressure in a shallow aquifer, as described in the following section. Many other examples could readily be cited, but these two local cases indicate the necessity of considering changes in the ground-water regimen as having a possible bearing on the Wilmington subsidence.

Effect of ground-water disturbance in 1941.—The construction of the U. S. Navy Graving Dock No. 1 on Terminal Island began late in 1940. In midsummer of 1941 the contractors began pumping water in large quantity from highly porous and permeable beds containing confined water below the bottom of the dock site.

Although thicknesses of the confined water-bearing beds and the relatively impervious layers bounding them above and below varied laterally, test holes at and near the dock site indicated a sequence approximately as follows:

Surface to depth of 55 to 75 feet below sea level: Very fine sand and silt, with clay streaks and sand lenses.

−55 or −75 feet to −115 feet: Permeable sand becoming coarser at depth with some gravel in lower part.

−115 feet to −125 or −130 feet: Rather dense silty loam and clay; rather impermeable.

−125± feet to −225 or more: Very permeable coarse sand and gravel.

This sequence is substantially as shown in the log of the Shuffelton Well (Edison No. 4) near the Channel to Long Beach Inner Harbor, Southern California Edison Company property just west of the entrance. Eastward from the County Flood Control Channel the shallow strata are finer-grained with fewer aquifers as shown by other logs.

Shortly after the dewatering pumps at the Graving Dock were put in operation it was noticed that the surface of the ground was subsiding. The cracking of oil-well foundations near the Graving Dock and the rapid decline in elevation of bench marks on the eastern part of Terminal Island prompted the Long Beach Harbor Department, the Southern California Edison Company, the Union Pacific Railroad Company, and others to run frequent spirit level lines between bench marks. Thus, the amount and variable rate of subsidence of numerous points near the dock site were determined. Grant made a detailed study of the situation during the summer and fall of 1941 (Grant, 1941). A plotting of the decline of these bench marks and rate of dock pumping showed a direct correlation between them, and also with the decline in static water level in Edison Company observation well No. 4. This well penetrates one of the aquifers below the Graving Dock, but the near-surface water of the semiperched water table is cased off. Thus the variation in pressure in the confined water body was reflected in the static water level in this well. Figure 14,

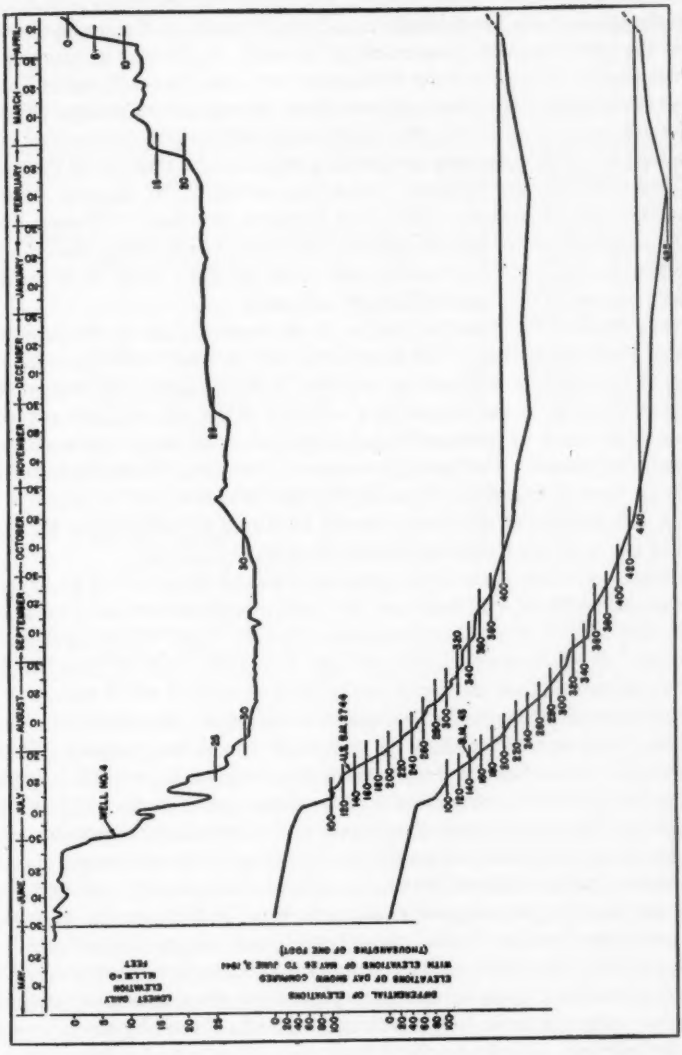


FIGURE 14.—*Water-level fluctuations and elevations of representative bench marks near the Southern California Edison Company Steam Plant during the dewatering of the near-by U. S. Navy Graving Dock, June 1941–April 1942*

here reproduced by the courtesy of the Southern California Edison Company, demonstrates the relation between the static water level in Edison well No. 4 and the elevation changes of two representative bench marks. It can be clearly seen that the decline in elevation of the bench marks was directly related to the decline in water pressure in the porous material penetrated by the well. A decrease in pumping rate reversed the trend. When the water level in the well rose, the bench marks likewise rose. This demonstrates that the aquifers possess considerable elasticity. Furthermore, the static water level in well No. 4 fluctuates directly with the rise and fall of the tide, a high tide adding an extra compressing weight on the strata from the surface down to and including the aquifers. According to Mr. R. W. Spencer (letter of June 19, 1945, to U. S. Grant), Chief Civil Engineer, Southern California Edison Company, in 1941 the water level in well No. 4 fluctuated in harmony with the tides over a vertical range 27 per cent of the tidal range, giving a value of 27 for what Jacob (1940) has called the "tidal efficiency" of a well.

These data demonstrate that the shallow aquifers penetrated by the dewatering wells possess elastic properties. The rising of the bench marks with the restoration of pressure in the aquifers, indicated by recovery of substantially the original static water level in Well No. 4, can be used as a criterion of the relative parts played by elastic compression and by a compaction due to flowage of cement between grains and grain rearrangement. The latter phenomenon is almost certainly irreversible so that elasticity alone is responsible for all of the partial recovery of elevation.

The most detailed data on elevation recovery have been furnished us by Mr. W. L. Chadwick of the Southern California Edison Company (Table 1).

The leveling upon which these figures were based was all referred to B.M. 18, on an unused transmission tower foundation on the south margin of Cerritos Channel and on the opposite side of the Edison Buildings from the Fleet Operating Base and Graving Dock. B.M. 18 no doubt subsided also during the Graving Dock construction, but at a lesser rate than the bench marks listed here, all of which are nearer the dewatering pumps and the locus of maximum subsidence. Therefore, the figures tabulated are based upon differentials between B.M. 18 and those named. Had an absolutely stable control been used the maximum subsidence value would have been increased, probably a few hundredths of a foot. Those bench marks which subsided most had the smallest percentage of recovery of elevation, and vice versa. This indicates that irreversible compaction due to mineral-grain rearrangement played a relatively more important role where the subsidence was greatest, and that where subsidence was least the percentage of recovery to May 12, 1942, was greatest; hence elastic recovery was greatest. Also, those bench marks on or at the large plant buildings generally subsided less than those some distance from the buildings. This variation in elastic recovery can be explained by the greater compaction of the sediments under the large, heavy buildings, caused not only by the extra static weight of the buildings, but also by the vibrations during pile driving for the foundations and the vibration of the buildings during occasional earthquakes.

The prompt reaction of the bench marks during this dewatering is worthy of emphasis. When the dewatering pumps were first put in operation, June 27, 1941, the hydrostatic pressure in the aquifer tapped by Well No. 4 almost immediately declined. On July 3, leveling indicated the bench marks had definitely dropped.

Thus the surface movement did not lag more than 6 days and may have been simultaneous with the drop in hydrostatic pressure. This prompt response of the surface could hardly have been primarily due to dewatering of clays, as water loss from materials of such low permeability, upon which their compaction depends, is a slow

TABLE 1.—

Maximum subsidence and recovery in elevation of bench marks at Long Beach steam station Southern California Edison Company

B.M. No.	Location	Maximum Subsidence	Recovery to Apr. 7, 1942		Recovery to May 12, 1942	
		Feet	Feet	Per cent	Feet	Per cent
5	Southeast Corner of Plant No. 1	.066	.013	20	.032	48
15	On South Wall of Plant No. 2	.046	.013	28	.033	72
16	Southwest Corner of Plant No. 2	.077	.030	39	.043	56
17	On West Wall of Plant No. 2	.072	.026	36	.039	54
28	Southeast Corner of Plant No. 3	.077	.030	39	.048	62
33	Northwest Corner of Plant No. 3	.076	.028	37	.036	47
37	Southwest Corner of Plant No. 3	.064	.037	58	.050	78
37A	South of Plant No. 3	.073	.035	48	.054	74
38	Southwest Corner of Switch Garden	.253	.030	12	.041	16
40	North of Tank Farm	.273	.025	9	.045	16
42	Corner of Tank Farm Pump House	.329	.037	11	.063	19
43	Southeast Corner of Tank Farm	.495	.042	8	.071	14
45	East of Tank Farm	.450	.039	9	.064	14
128	Oil Well South of Plant No. 3	.126	.035	28	.059	47
134	Oil Well Southwest of Plant No. 3	.192	—	—	—	—
U.S. 2742	South of Plant No. 3	.121	.034	28	.055	45
U.S. 2743	Southwest of Plant No. 3	.187	.039	21	.060	32
U.S. 2744	Southwest of Plant No. 3	.454	.041	9	.070	15

process. Furthermore, on July 15 and 16, 1941, the pumping rate at the dock was materially reduced. This was reflected in a 7-foot rise in the water level in Edison Well No. 4. During this period, spirit leveling was carried on every 2 or 3 days. A most significant phenomenon detected by this intensive surveying was the prompt response of the bench marks to the partial recovery of hydrostatic pressure in the aquifer. Several bench marks rose .01 to .02 foot, indicating partial elastic recovery of the aquifer. This prompt recovery could hardly have been due to swelling of clay in response to increased water pressure in adjacent sands. It has already been mentioned that this aquifer records the rise and fall of tides. We therefore conclude that the subsidence and partial recovery at the time of the Graving Dock construction was largely if not wholly due to the compression of the aquifer itself rather than of the adjacent poorly permeable clay beds.

Although this subsidence was small, both in amount and in area affected, it was so dramatically and unmistakably associated with the lowering of water pressure in the aquifer that it becomes imperative to ascertain in what degree such a mechanism might have operated to produce the more widespread subsidence with which we are primarily concerned.

Regional changes in regimen of confined ground water.—No drastic changes in

regimen of the confined ground water may be correlated either areally or in time with the development of the Wilmington oil field. Drilling practice calls for cementing both conductor pipe and surface string promptly and any effects of drilling on the aquifers in the first thousand feet of subsurface are negligible. The water production ("water-cut") from the oil sands is extremely low. Nearly all the wells are gun-perforated, and the water sands directly tributary to the wells are of negligible thickness. Accordingly, we believe it is most improbable that any appreciable part of the subsidence centering in the field is attributable to changes in ground-water regimen. The long-term decline of the piezometric head of the aquifers in the Los Angeles Basin may contribute to the more widespread subsidence of the general coastal area.

Ground water in the coastal plain of Los Angeles and Orange counties has shown an irregular but progressive decline in amount since 1860 (Mendenhall, 1904; Meinzer, Wenzel, and others, 1944; Eckis, 1934; Water Department, City of Long Beach, 1944; Piper, Poland *et al.*, 1945). There are only fragmentary records of the decline in level of the water table in shallow water-table wells, but the records of static water levels in aquifer (artesian) wells are voluminous. Mendenhall (1904) mentioned the decrease in artesian area prior to 1904, and there has been such an increased use of ground water since then that few wells in the Los Angeles County and Orange County plain are now flowing at the casinghead. In 1904 the piezometric surface of the confined water bodies was considerably above sea level easterly from the Newport-Inglewood uplift and somewhat lower west of that zone. While no accurate general figure can be given for the entire area, the decline in piezometric level has been of the order of 25 to somewhat more than 75 feet during the last 4 or 5 decades. In general, the decline has been less seaward, but irregularities are present, and as the annual fluctuation ranges between 10 and 20 feet they are difficult to average.

The greatest known decline in pressure head occurred at the Bouton group of wells about 2½ miles north of Signal Hill. The so-called "Big Bouton Well" was drilled in 1891 and came in with an initial pressure of 35 pounds per square inch at the surface (Long Beach Water Department Report, 1944, p. 26–27, Fig. 4; Piper, Poland, and others, 1943, p. 3). The surface elevation here is about 70 feet above sea; the static level was thus about 150 feet above sea. Water flowed from this well in 1916 for the last time; by the summer of 1944 the static level was 106 feet below ground surface, a drop of 186 feet in pressure head since 1891. This is the greatest pressure decline known in the area and hence should give a measure of the maximum subsidence that could be expected from this cause. The aquifer penetrated is about 40 feet thick (Poland and others, 1942, p. 14). If it be assumed that the aquifer has a modulus of elasticity as low as 10,000 p.s.i. then the total elastic compression would be .33 foot or 4 inches, during the 50 year period. Of this, less than .04 foot could be attributed to decline of the last 10 years.

As the decline at the Bouton well is the greatest in the area, it might be concluded that the elastic response of aquifers in the Harbor area to the much smaller lowering of the piezometric levels in that area is a minor factor. However, some of the aquifers are considerably thicker than that tapped by the Bouton well. Furthermore, grain rearrangement (plastic deformation) would be additive to the elastic shortening and,

to judge from the behavior of the aquifers penetrated by the dewatering pumps at the Navy Graving Dock in 1941, might be expected to be roughly equal to it. (*See* Table 1, which shows ratios of elastic to plastic deformation ranging between 14 and 78 per cent.) It might be expected that grain rearrangement in response to such slight pressure changes would be relatively much less in deep than in shallow aquifers because the process must take place more or less *pari passu* with the addition of superincumbent sediments and hence have been further advanced in deep than in shallow sands. A factor probably more important in deep aquifers, however, would be the loss of water from adjacent clays to the aquifer, with consequent shrinkage of the clay sections. This factor can be sharply discounted at Terminal Island, however, because: (1) the piezometric lowering has been slight in the last 40 years; (2) few aquifers occur toward the eastern part of the subsiding area; and (3) the rapid decline of surface does not correlate in time or proportion with the lowering of piezometric surface in the region as a whole or locally. However, this process of dewatering of clay as the piezometric surface declines cannot be ignored as a factor in producing the broader regional subsidence of a few tenths of a foot and indeed may contribute notably to it.

As dewatering of clays adjacent to aquifers that are undergoing pressure decline has been apparently quite important elsewhere (Tolman and Poland, 1940) it demands further consideration. Loss of water from the clay is a function of permeability, pressure gradient, and time (Terzaghi, 1943, p. 265–296). The permeability transverse to stratification is always less than parallel to it; accordingly one would expect the process to be more rapid in lenticular sediments than in continuously even-bedded strata. Data are inadequate for a quantitative analysis of the local situation. However, it is perhaps significant that a slow, slight subsidence of generally the same amount as in the rest of the region (except for the much greater subsidence at Wilmington which is the primary concern of this paper) has also taken place in the Long Beach business district where there are not only few aquifers but they are thin and have been very little pumped in recent years. Available data do not suffice to determine how much of the slow regional subsidence of a few tenths of a foot is due to tectonic forces, how much to decline in pressures of shallow aquifers, and how much to decline in pressures of deep edgewater aquifers between the several oil fields. A reasonable conclusion from what is known would seem to be that changes in the regimen of shallow aquifers have played a minor, though not a negligible role in the regional surface subsidence.

In the Harbor area where the marked subsidence has been localized, though accurrate estimates are out of the question, the cumulative subsidence from lowering piezometric surfaces in the shallow aquifers can hardly have exceeded 0.2 foot in 4 or 5 decades and must have been far less in the 10 years of active ground recession. The current decline in well production and the importation of Colorado River water to the Los Angeles Basin suggest that future subsidence from this cause will be trivial.

Effect of water-table fluctuations.—The data on changes in position of the water table in the Long Beach area are meager compared to those for the piezometric level of the ground water confined in aquifers. In general the level of the water table has fluctuated very little in the low area near the harbor.

During normal conditions preceding the large amount of war construction on Terminal Island the water table was generally a few feet above mean sea level. Fluctuations in the position of this water table, under normal conditions, appear to be limited to a vertical range of 2 to 4 feet, except during periods of heavy rainfall when, locally, the water table rises to the surface. As much of the surface of the eastern part of Terminal Island prior to war construction, and before the major part of the recent subsidence had taken place, was only 6 to 8 feet above mean sea level, the maximum fluctuation in the water table could not have been greater than about 6 or 7 feet.

The drying and concomitant shrinkage of dredged material used in reclaiming tidelands or as fill on the original surface may, of course, cause local subsidence, but the general rapid subsidence with which we are concerned involves a larger prism of naturally deposited material than it does of fill—and in fact is greater elsewhere than on most of the "made land" of Terminal Island.

In conclusion, fluctuations in the water table have had a negligible bearing on the general areal subsidence of Long Beach Harbor.

INFLUENCE OF INCREASED LOADS ON THE SURFACE

In the Long Beach Harbor area increased loads have locally been placed on the surface by fill and by the construction of buildings. Buildings commonly settle because the underlying sediments slowly consolidate, particularly where clay is present beneath the foundation. The National Theatre in Mexico City furnishes a classic example of such subsidence, one column having sunk 5 feet in 9 years. This large subsidence was local, but the entire area of the City of Mexico is also subsiding—the greater subsidence beneath large buildings are small dimples in a large saucer-shaped depression. Cambridge, Massachusetts, is said to have subsided areally a maximum of 2 feet between 1896 and 1909 (Terzaghi, 1938). These two cases of areal subsidence beyond the limits of a single heavy structure are due to subsurface geological conditions particularly conducive to consolidation. An extensive stratum of weathered and highly plastic water-soaked volcanic ash underlies Mexico City, and the consolidation of Quaternary clay beneath Cambridge is believed to have brought about the subsidence on both sides of Massachusetts Avenue with its numerous business blocks.

These examples, to which others could be added, are in no way similar to the subsidence with which we are here concerned. At Long Beach the maximum subsidence shows no correlation with the distribution of large structures nor does the rate of subsidence correlate with the time of construction of heavy buildings. The great wartime development in Roosevelt Base on Terminal Island partially coincides in time with accelerated subsidence, but a study of the isobase charts shows no reflection of the development of Roosevelt Base nor other localized areas of new structures. Nevertheless we have computed the approximate weight of the dredgings pumped into the area of the base. Using approximate dimensions furnished by Mr. C. L. Vickers of the Long Beach Harbor Department, the total dry weight of the fill amounts to a little less than 12 million tons. However, the outer portion of the fill was deposited in the sea to a maximum depth of about 20 feet below mean sea level,

thus reducing the weight of the added load by about 1¼ million tons. If the dimensions furnished us are moderately accurate, the average weight per unit area of the additional load is less than 1 ton per square foot. Even if this figure is in error by as much as 25 per cent, the additional weight is so small that only a local subsidence limited to a horizontal distance of but a few feet from the limits of the fill could possibly be due to this overburden. The fact that the subsidence is not so great at the Naval Base as it is at Channel No. 2 rules out the fill as a major factor.

The subsidence of the harbor district, involving much area not subjected to additional loads during or immediately before the time of highest rate of subsidence, cannot be attributed to surface loading.

EFFECT OF OIL-FIELD OPERATIONS

Introduction.—Among the artificial changes that have taken place in the harbor area is the development of the Wilmington oil field. The possible effect of oil withdrawal and accompanying phenomena is especially suggested by the coincidence in both place and time of the rapid subsidence with the exploitation of the oil field. Among the factors that might be considered operative are: (1) the extraction of oil, with the consequent sinking of the surface to fill the potential voids thereby formed; (2) the additional load imposed upon the reservoir sands by the extraction of their oil and gas, and consequent loss of hydrostatic pressure within them; and (3) the loss of water from adjacent beds to the oil sands as the pressure within them declined, thus permitting dehydration of adjacent clay beds.

These factors are all discussed as completely as available data permit, and it is concluded that the extraction of oil did not, in itself, bring about the subsidence, but that the loss of pressure in the reservoir sands and the additional load that this imposed upon the sands is qualitatively adequate as a mechanism to bring about the observed subsidence. Furthermore, the known quantitative aspects yield theoretical results in close harmony with the actual subsidence. When the coincidence in time between the subsidence and the decline in reservoir pressure is considered in conjunction with these results, the conclusion that most if not all of the subsidence is due to this cause becomes strongly fortified.

Relation of subsidence to volume of oil removed.—Although cores from the oil sands of the Wilmington oil field are coherent and the sand production from the wells very moderate, it might be thought that the subsidence shown at the surface is the result of settling into voids left by removal of oil from the field. This would imply a sort of "oil quick-sand" for the oil-producing beds and is *a priori* very improbable. However, it was thought worth while to investigate the question quantitatively.

Total production for the four eastern blocks—in which the subsidence is most pronounced—was converted into cubic feet of oil. It proved impossible, with the data at hand, to compute the volume of gas produced with the oil, but this was largely dissolved in the oil before development. A rough calculation of the area of each of these blocks was made, and the volume included between the original surface, as of 1934, and the surface as of 1945 was also computed for each block. This volume was computed according to the isobase map prepared by Mr. Vickers (Fig. 6) and also according to the isobase map prepared by us (Fig. 7). The results of these computa-

tions are shown in Table 2, which shows that there is no evident relation between the volume of oil produced from a given block and the volume of subsidence within it. Thus the subsidence is seemingly not due in any significant degree to settling into voids left by the extraction of the oil from the field.

TABLE 2.—*Comparison between volume of oil produced and volume of subsidence Wilmington oil field, by blocks*

Block	Area M ft.	Production M Bbls.	Production cu. ft. × 1000	Depth oil as layer	Volume of subsidence (Vickers)	Volume of subsidence (Gilluly, Grant)	Ratio, volume of subsidence to volume of oil removed	
							Vickers	G. and G.
				feet				
II	36295	34135	191156	5.26	68017	77183	.358	.404
III	43940	17615	98638	2.24	114670	114739	1.164	1.163
IV	36130	79727	446471	12.36	101923	92638	.228	.207
V	38610	25200	141120	3.66	103322	189493	.731	1.346

Relation of subsidence to loss of pressure in oil sands.—Prior to drilling, the Wilmington oil field contained many hundred feet of oil-bearing sandstones, separated and overlain by practically impervious shales. These rocks were all deposited in the sea, the total time required for their accumulation running to several millions of years. Under these conditions, the permeabilities of the several strata could have little or no effect on the hydrostatic pressures prevailing in any given bed, especially as none of the strata involved are known to crop out at higher elevations. At any given depth the hydrostatic head of the fluids was roughly equivalent to the head of a column of salt water extending from sea level to that depth. In other words, the pressure gradient of the fluids had no relation to the permeability of the rocks.

At any given depth, the static load due to overlying rocks can be fairly accurately computed by assuming that the average rock has a grain density of about 2.7, a porosity of 35 per cent, and its pores are filled with sea water of a density of 1.027. Under these assumptions, the static load due to the rock at any given depth, is that shown by Curve A, (Fig. 15). This curve is the graph of the equation:

$$P = \frac{D \times 62.5 \times .65 \times 1.7}{144}$$

in which P is pressure on a horizontal surface in pounds per square inch,
D is the depth in feet,
62.5 is the weight of 1 foot of water,
.65 is the volume ratio of grains to total volume of sediment,
1.7 is density of grains minus bouying effect of water, and
144 is the area of 1 square foot, in inches

When an oil sand, capped with a shale bed of low permeability, is tapped and the pressure within it reduced, the buoying effect of the interstitial liquid is no longer effective to support the load on the top of the sand bed. As a result, the effective

weight of the overlying column is no longer supported in part by the hydrostatic pressure on the bottom of the shale and tends to approach the values given in Curve B of Figure 15. This curve is the graph of the equation:

$$P = \frac{.65 \times 2.7 \times 62.5 \times D + .35 \times 64 \times D}{144}$$

in which the .65 and the .35 are the respective volume ratios of grains and water,
62.5 the weight of a cubic foot of fresh water,
64 the weight of a cubic foot of sea water,
2.7 the specific gravity of the sand grains,
D the depth, and P the pressure on a horizontal surface in pounds per square inch.

Theoretically, this equation gives the maximum load per square inch that can be placed upon an impermeable membrane at the given depths. The difference, on the stress axis, of the values for curves A and B for a given depth is the additional load that could theoretically be placed upon the rocks at that depth by the reduction of the fluid pressure within them to atmospheric pressure. The depths from which the several cores tested for this report were taken are indicated on this figure. From these graphs can be read the potential stress addition that could operate on the sands represented by several cores. Even at the greatest depth in the field, this possible load increment is still less than 2000 p.s.i. and therefore much less than the stresses used in our testing of the cores. At Wilmington, then, the extraction of oil and gas from the oil sands permitted the pressure at the well bottom to diminish. The pressure distribution changed from one of hydrostatic equilibrium to one involving hydrodynamics. About each well there developed a pressure gradient, steep or flat, depending on the rate of production, time of production, viscosity of the oil contained, and the permeability of the oil sand penetrated. For the most part, such pressure gradients would be limited to individual strata, for the permeability of the shales interspersed with the oil sands is probably so low that the pressure drop within them is probably not yet very important, even around the older wells in the field. If one considers the mechanics involving a single stratum in which the fluid pressure is markedly diminished, it can be seen that originally the load of overlying strata was in part supported by the hydrostatic pressure within the oil sand. Release of this pressure, then, is tantamount to increasing the load acting on the stratum concerned. Inasmuch as the pressure drop within individual sands has been several hundred pounds per square inch, and these pressure drops have occurred throughout thick zones of the oil field, the column of rock within which the pressure drop occurs must be compressed somewhat under this increased load. To investigate the quantitative aspects of this mechanism, it was necessary to gather data of several kinds: pressure changes, thickness of oil sands affected, and the mechanical properties of representative sands. None of these factors provides precise objective values. However we

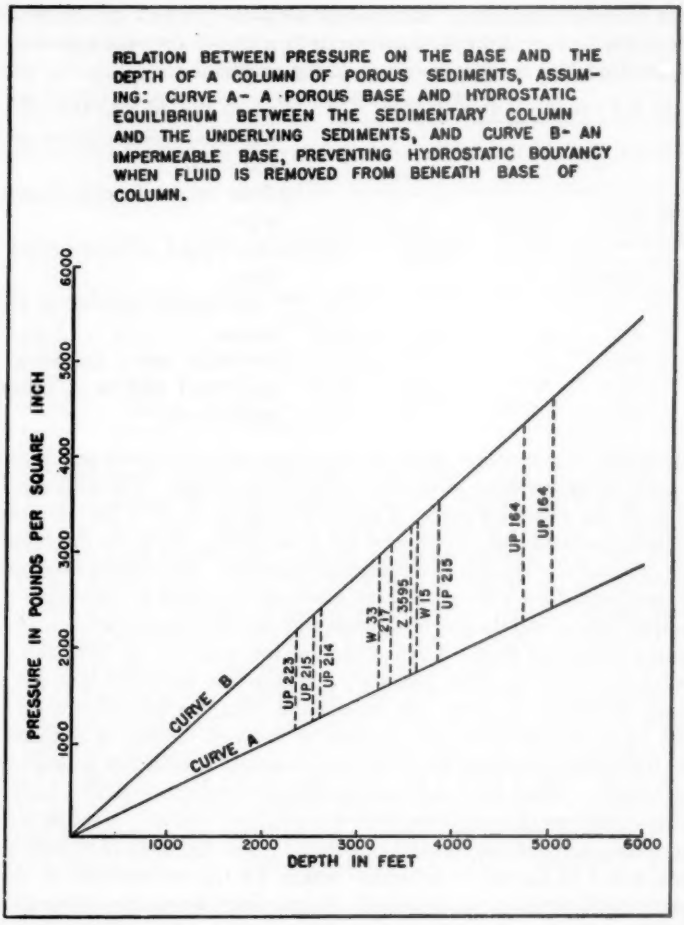


FIGURE 15.—*Chart showing relation between depth of a column of porous sediments and the pressure exerted on its base (the underlying strata)*

Assuming: (Curve A) a permeable base with consequent hydrostatic equilibrium of fluids within the column and in the underlying strata; (Curve B) an impermeable base, preventing hydrostatic buoyancy of the overlying column when the fluids are removed from the strata beneath the impermeable bed at the base of the overlying column.

are not reduced to pure conjecture as to the effects to be expected. The data available permit certain fairly definite conclusions as to the expectable results, and in the sequel these are compared with the subsidence data as shown by Figures 6 and 7.

DATA ON BOTTOM-HOLE PRESSURES: Several of the operating companies in the field permitted the use of bottom-hole pressure data only on the condition that it not be identifiable as to an individual well. For many wells few measurements are

available; for others the rate of change of pressure with time is rather erratic, and the reduction of the pressure changes to a common datum and common date—January 1945—required considerable extrapolation. For these reasons, as well as

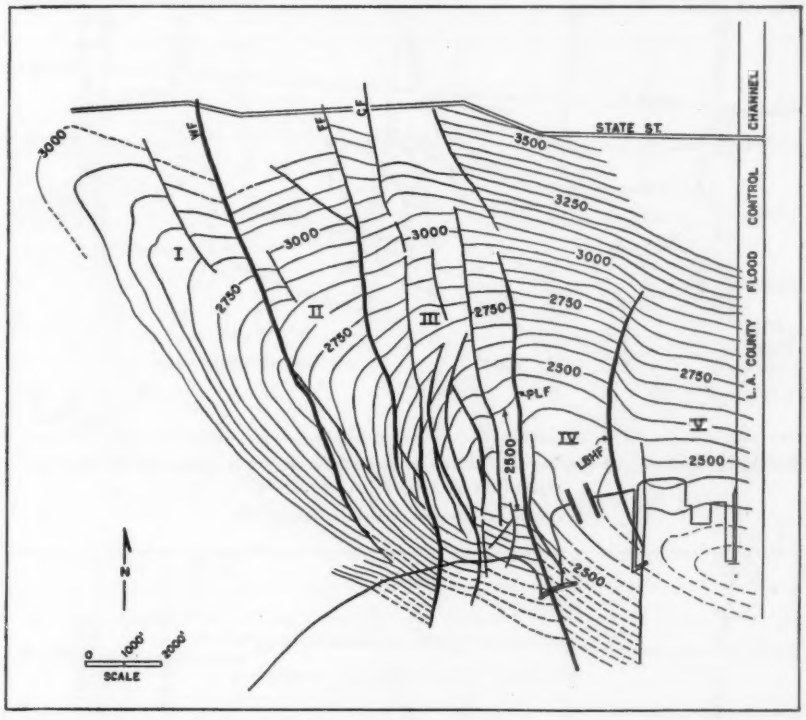


FIGURE 16.—*Structure contours on the "F" marker, Ranger zone, Wilmington oil field*

Modified from compilation by Wilmington Field Engineering Committee, Nov. 1943. Roman numerals indicate blocks locally used in compiling production data.

complete lack of data from parts of the field, detailed accuracy cannot be claimed for the pressure decline data obtained for the field. However, as will be clear from the later charts and discussion, no reasonable change of the pressure data as shown in Figures 17, 18, and 19 would affect the results of the computation very greatly.

Figure 17 shows the pressure decline in the Ford zone, reduced to datum of −5200 feet and a date of January 1945. From this, though the lines of equal pressure decline are of necessity generalized, it can be seen that the decline ranges from about 100 pounds per square inch to as much as 1900 pounds per square inch. Figure 18 shows similar data for the Terminal zone, and Figure 19 for the combined Tar-Ranger zones. With each of these charts a similar limitation must be noted: their accuracy in detail—because of local cones of depression about individual wells, in-

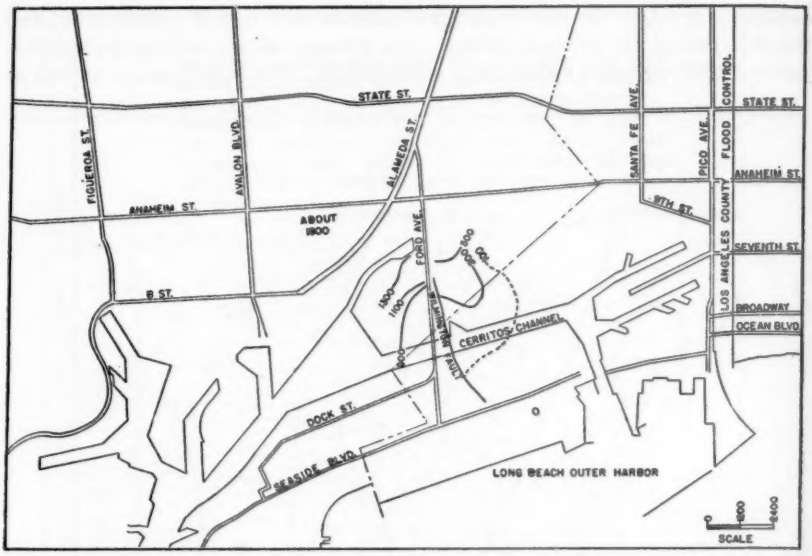


FIGURE 17.—*Isopleth map showing distribution and amount of reduction in pressure in the "Ford zone", Wilmington oil field, to January 1, 1945*

As extrapolated from measurements at various times

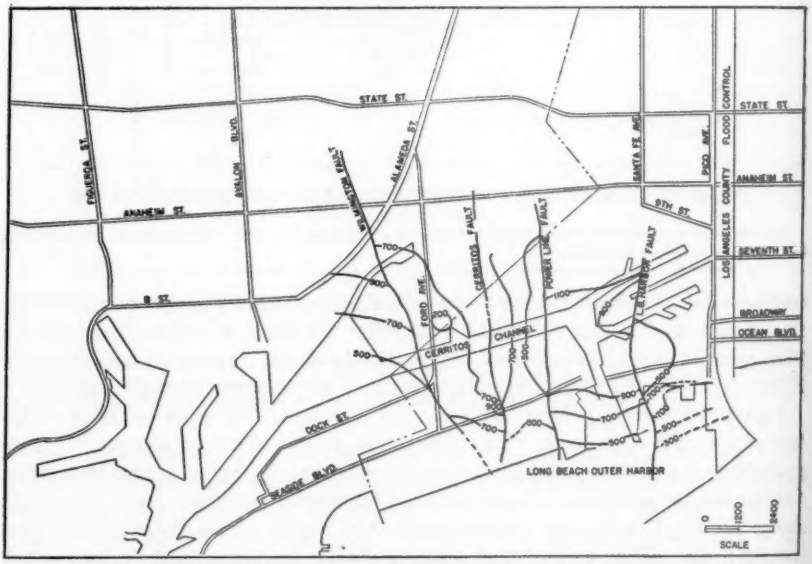


FIGURE 18.—*Isopleth map showing distribution and amount of reduction in pressure in the "Terminal" zone, Wilmington oil field, to January 1, 1945*

As extrapolated from measurements at irregular times

adequately distributed data, both in time and place, and complete lack of data from certain wells—cannot be vouched for. Nevertheless, they present a body of information that must carry great weight because, whatever modifications additional homogeneous data might require, the fundamental facts that significant pressure

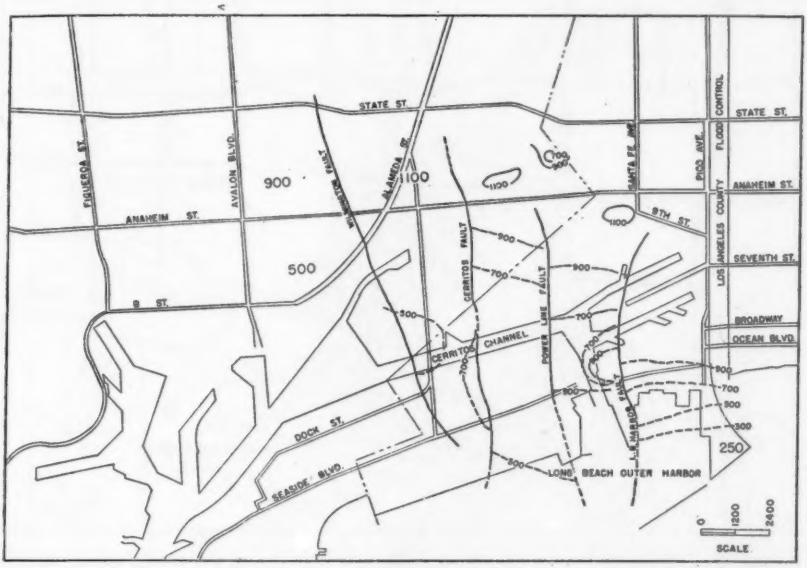


FIGURE 19.—*Isopleth map showing distribution and amount of reduction in pressure in the "Tar-Ranger zone", Wilmington oil field, to January 1, 1945*

As extrapolated from measurements at irregular times

decline has taken place within the oil sands and that this decline has been roughly of the amounts indicated must be in essence correct. As will be shown subsequently, it would be necessary to assume that these maps are in error by as much as 50 per cent to 75 per cent to vitiate the argument derived from them. It is confidently believed that modifications that would be necessitated by complete and homogenous data would not change the picture given by these maps by more than perhaps 10 per cent, though individual readings might be changed much more.

DATA ON THICKNESS OF OIL SANDS: Equal in importance with the pressure data are the data on thickness of the sands within which the pressure decline has occurred. This is a complex and subjective problem, because throughout the field the oil zones consist of interbedded shale, sandy shale, shaly sand, and sand, of very widely ranging permeability and hence wide range of susceptibility to the transmission of pressure changes across and along the stratification. An attempt was made to evaluate the sand percentages within each zone from the electric logs of the wells, but this was abandoned, both because of the magnitude of the task of studying the hundreds of logs and because of the personal equation involved in the interpretation. It was finally decided that the most objective way of appraising this matter was by using

the thicknesses of strata within which the casings have been perforated in the several oil zones. The perforations in an individual well are made with care, from study of the electric logs by men usually familiar with the local characteristics of the strata

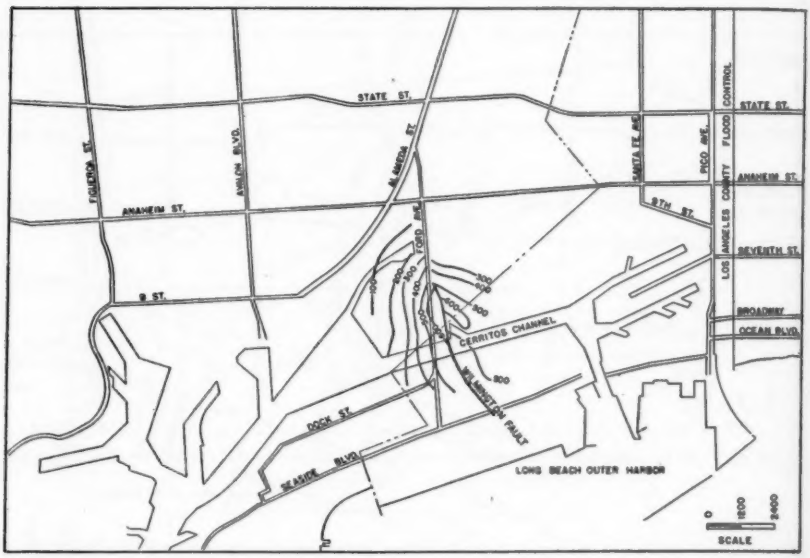


FIGURE 20.—*Isopachs showing the approximate length of perforated casing (thickness of zone of reduction of fluid pressure) in the "Ford zone", Wilmington oil field*

involved, and may consequently be regarded as rather objective appraisals of the oil-sand intervals encountered by individual wells.

As with the pressure data, no very high degree of accuracy in details can be claimed for the isopach maps. In Figures 20, 21, and 22 are shown lines of equal length of perforations in the Ford, Terminal, and Tar-Ranger zones, respectively. Certain vagaries of these lines may be due to lensing of beds, *i.e.*, real differences in the thickness of oil sands, and some to a differing appraisal of the economics of producing from certain intervals. Others are due to the edgewater which dictated the perforation of only the upper part of a zone in a border well, though the entire sand may extend as a water sand beyond the limits of the field, and the pressure drop within it may affect a considerably greater thickness than the perforated interval. It is believed, however, that there is enough shale in the section generally to inhibit the transmission of pressure changes from bed to bed except for short intervals. It is accordingly justifiable as a first approximation to use the thinned zone of perforations even in the edgewater wells as a measure of the thickness of rock subjected to increased load by the diminution of hydrostatic pressure within it. Certain contours might be placed somewhat differently by other geologists, but, again, the actual conditions must be very similar to those portrayed in these charts, and gross errors sufficient to vitiate their usefulness are not believed to exist.

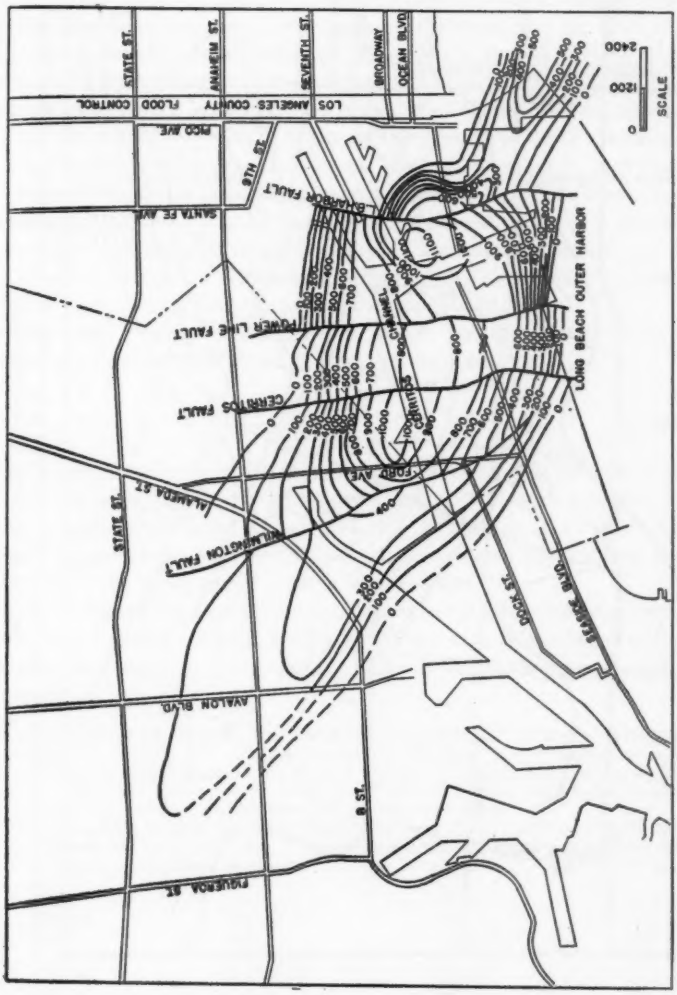


FIGURE 21.—*Isopachs showing the approximate length of perforated casing (thickness of zone of reduction of fluid pressure) in the "Terminal zone", Wilmington oil field*

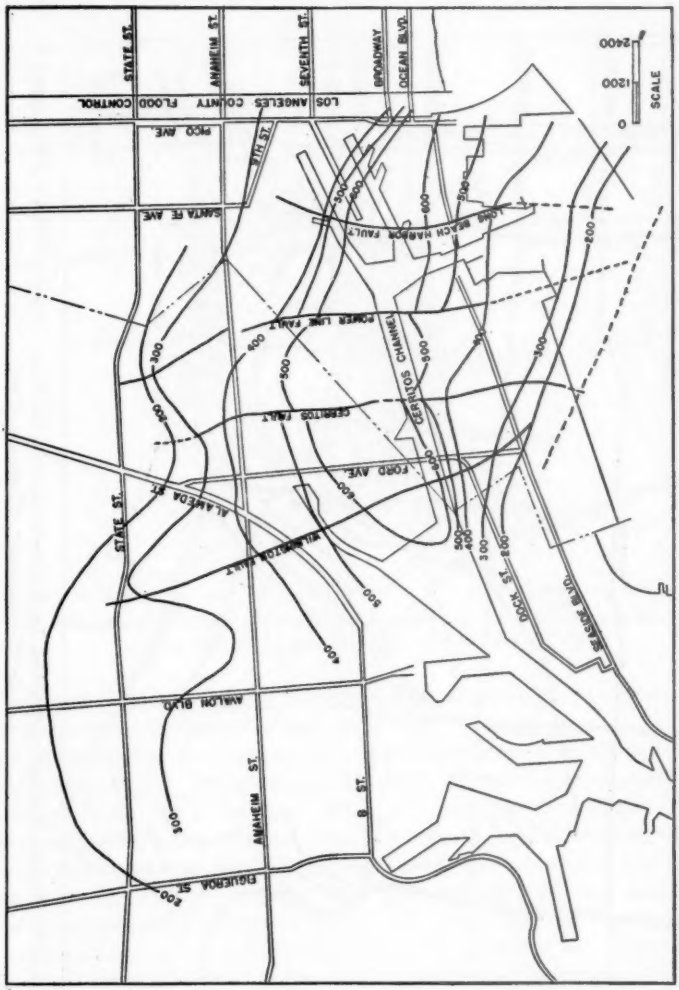


FIGURE 22.—*Isopachs showing the approximate length of perforated casing (thickness of zone of reduction of fluid pressure) in the "Tar-Ranger zone", Wilmington oil field*

These charts require an additional word of explanation. Within the perforated zones there are known to be considerable thicknesses of shale, shaly sand, and silty sand of varying permeability. Certainly not all of the perforated zones have undergone so great a pressure change as the better-producing strata whose pressure changes probably dominate the data. The pressure measurements are after all hydrodynamic rather than hydrostatic records. Accordingly, the use of these thickness data in computing the subsidence to be expected from loss of pressure in the oil sand would probably yield results somewhat too high. Insofar, however, as pressure changes may be transmitted from bed to bed across the strata—a factor that may be important, particularly in the edgewater areas—the results would be somewhat too low. On balance, this factor probably does not compensate for the other, and the true stratigraphic thickness affected by pressure decline is probably somewhat less, on the average, than that shown on the charts. In a following section it is shown that a considerable margin for error exists, within which any reasonable independent appraisal of these factors would not affect the conclusions.

MECHANICAL PROPERTIES OF THE OIL SANDS: The shortening, within the elastic limit, of any material under load, is given by the equation:

$$\frac{l_o - l_s}{l_o} \times E = P_s - P_o$$

in which l_o is the original length, p_o is the original stress, l_s is the length under a different stress, p_s is the corresponding stress, and E is Young's modulus. This is, of course, a familiar expression of Hooke's Law. In order to apply this to the problem in hand, it is necessary to determine the elastic constants applicable to the oil sands within which the postulated change in length occurs.

Eleven samples from sound cores of oil sands in the field were examined and tested under compression by Professor Wendell E. Mason of the Department of Engineering, University of California, Los Angeles. Professor Mason submits the following note on the tests:

"The cores for these tests came to us in such sizes that it seemed best to dress them to three diameters, namely 1¾″, 2½″ and 3¼″. The cores were carefully fitted in steel sleeves, with steel plugs at either end. Longitudinal pressure was applied through the plugs by means of a hydraulic testing machine. The sleeves were heavy enough to effectively prevent diametral deflection, but such deflections as did occur were corrected for in calculating the strains.

"The longitudinal deflections were measured by means of three dial indicators attached at 120° intervals around the upper steel plug. They measured the relative motion between the two plugs, from which gross strains were computed."

Z 3595	3568 ft.	3¼″ dia.		3 7/16″ long
UP 214	2578–2603	3¼″ dia.		1 11/16″ long
W 15	3600	1¾″ dia.		2 13/16″ long
W 33	3205–3213	1¾″ dia.		3 9/16″ long
UP 164	5029–5039	1¾″ dia.		3 13/16″ long
UP 215	2546	3¼″ dia.		2 13/16″ long
UP 223	2334–2354	3¼″ dia.		1 9/16″ long
UP 215	3840–3865	2½″ dia.		1 13/16″ long
UP 164	4700–4720	2½″ dia.		3 15/16″ long
UP 164	4700–4720	2½″ dia.		3 15/16″ long
M217	3359–3379	2½″ dia.		3 15/16M″ long
Sleeve diameters		Inside	Outside	Wall thickness
		3¼″	4½″	⅜″
		2½″	3 15/16″	11/32″
		1¾″	2⅞″	¼″

Graphs representing the relation between the stress acting upon the specimen and the resulting strain for each test are reproduced here as Figure 23.

Interpretation of these graphs is considerably more complex than the interpretation of stress-strain diagrams of many materials. The cores represent inhomo-

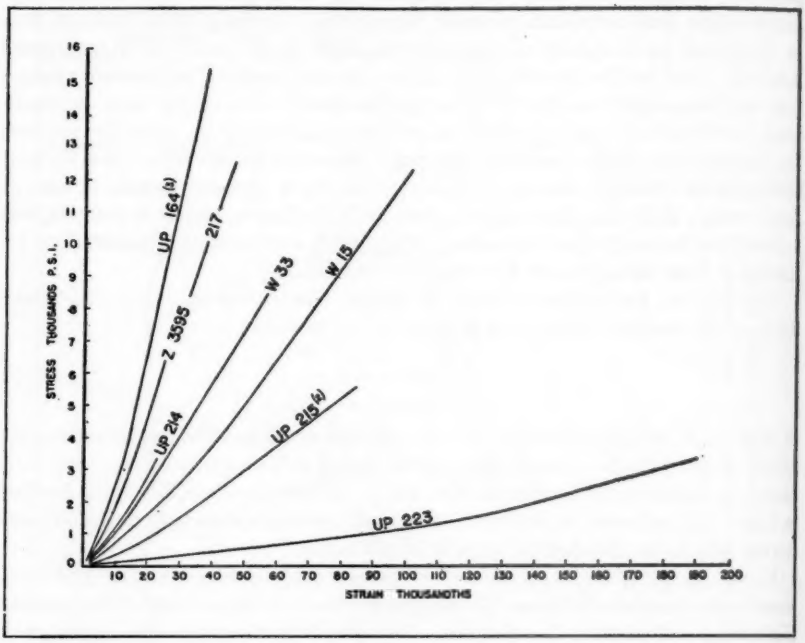


FIGURE 23.—*Stress-strain relations under compression of sandstones from the several oil zones, Wilmington oil field*

The zones from which the specimens were taken are as follows: Ford zone; UP 164; Terminal zone: Z3595, W33, W15, UP 215, 217; Tar-Ranger zone: UP 214, UP 223.

geneous, porous substances, and the application of principles worked out from massive continua, such as the metals, requires considerable modifications analogous to those employed in soil mechanics (Krynine, 1941; Terzaghi, 1943). Each of the specimens exhibits very marked hysteresis; that is, the stress-strain curve for declining stress is offset with respect to that for increasing stress, and the final value after a cycle is never zero strain.

In other words, every cycle results in a permanent (plastic) deformation. Repeated cycles show a continuation of this phenomenon, with only slight diminution of the strain for each successive cycle. Each of the ascending curves rises more steeply than that of the preceding cycle, illustrating the phenomenon of "elastic gain." A second feature of the curves is a continuous deformation at constant stress, clearly an example of flowage. There is little doubt that this accounts for a large

part of the hysteresis. Even during decreasing stress, above a threshold value, the flowage persists and counteracts, in part, the elastic response to the lessening stress. This accounts for the steeper upper portions of the curves for declining stress. From all these considerations, even those parts of the ascending branches of the curves that are essentially straight—*i.e.*, those parts within which Hooke's Law might be regarded as holding—do not furnish a true value of Young's modulus, for in addition to the elastic factor the curves show a relation between strain and time of stress which is the criterion of flow. In general the rate of increasing stress was essentially uniform for each test so that the stress-strain diagram integrates truly elastic and truly plastic deformation almost, if not quite, inextricably. It is clear from the shape of the curves that flowage is important in all the cores tested, above a threshold value of stress somewhere between 1000 and 2000 p.s.i., *under the conditions of the tests.*

A rational explanation of these features can readily be offered, though there are many quantitative uncertainties which the testing equipment available does not permit evaluating. Each of the specimens is a sandstone, consisting of grains of quartz, subordinate feldspar and other minerals, with an admixture of clay and silt, held rather firmly in a calcite cement. The individual grains of this aggregate are highly elastic (except for the cement and clay minerals) and have moduli much greater than any shown by the cores. However, the clay minerals are very plastic, and calcite twins and glides under pressure. The original porosity of the sands tested ranges from 24 to 36 per cent, so there is considerable space within the framework of the sand aggregate for material to flow when the stress is increased. Though the average stress acting on the core cross sections during these tests did not in any case exceed 29000 p.s.i., and in most tests was much lower, the stress on the points of contact of the individual grains must have been considerably higher, and adequate to bring about permanent deformation of the matrix material, with which naturally some readjustment of the elastic grains must also have occurred. This is shown by the absence of fracturing of the cores and their decreased porosity after testing. With each cycle of repeated stress, a larger proportion of the clay and calcite would flow into protected places within the framework of the more rigid grains, leading to higher moduli and less permanent deformation after each succeeding cycle. The limits to which this process may proceed are further discussed.

Despite these complexities, it is believed that the tests furnish useful information as to the response of the rocks to changing load. In the short time, measured in hours, during which the laboratory tests were run, the flowage factor contained in the stress-strain diagram is much smaller than it is in the Wilmington oil field, where comparable stresses have operated for several years. On the other hand, the existence of this flowage leads to a flattening of the curves and hence to an ostensible value for the compression modulus that is lower than the true value. In a way, then, the two factors of elasticity and plasticity which are combined in the stress-strain diagram counterbalance each other. If the relatively straight portions of the ascending branches of the diagrams are used to compute Young's modulus on an arbitrary assumption of elasticity, it will yield values that are too low. Such values, when utilized as a measure of the response of the oil sands to changes in pressure, will give too high a value for the shortening of the beds under load. On the other hand, the

use of such values and the implied assumption that the entire response of the oil sands is elastic is equivalent to assuming that there has been no plastic deformation. The history of the subsidence in the field, which has apparently gone on at an increasing rate with time, confirms the testimony of the diagrams that a large part of the response of the sands to stress is actually by flowage. Accordingly, the too-low values of compression modulus are fair, though crude, first approximations of the expected deformation of the beds, although they combine both truly elastic and truly plastic components and are treated in the sequel as constants, whereas it is certain that a time factor is involved.

Thus, despite their limitations, it is believed that the compression tests furnish a useful yardstick for evaluating the expectable response of the oil sands under the changed pressure conditions due to the exploitation of the oil field. Figure 23 shows the increasing branches of the stress-strain diagrams of the several cores tested. The significant feature of these graphs is the slope of a line, not its absolute position, for the lower ends of the graphs are highly uncertain because of the conditions of the tests. The slope of one of these lines, in its straight portion, is a measure analogous to Young's modulus, which we call "compression modulus" and has been computed for each of the specimens.

$$\textit{Compression modulus} = \frac{P_s - P_o}{\dfrac{L_s - L_o}{L_o}}$$

The results of these computations are:

Well	Zone	Depth	Compression modulus
		feet	*pounds per square inch*
UP 164	Ford (zone)	5030	458,300
Z 3595	Terminal	3568	290,000
UP 214	Tar-Ranger	2578–2603	146,000
W 33	Terminal	3205–3213	162,000
W 15	Terminal	3600	139,000
UP 215	Terminal	3840–3865	72,700
UP 223	Tar (zone)	2334–2354	27,500
217	Upper Terminal	3359–3379	290,000

The range in modulus is very considerable. As would be expected, the higher moduli are in general those of deeper cores, though there is no direct correlation between depth of burial and modulus. To get a rough approximation of the subsidence that would be expected due to lessening of pressure in each of the zones, the single value for the Ford zone, 458,300 p.s.i., was assumed to apply to that zone, the mean value of 166,000 p.s.i. was used for the Terminal zone, and the higher of the two values of the modulus for the Tar-Ranger zone, 146,000 p.s.i., was used for that zone.

Application of Data to the Wilmington Oil Field: Only long-term tests could give results directly applicable to the field conditions. Such tests could not be made with the equipment available. Nevertheless the data gathered are roughly usable in estimating the effect of the virtual increased load on the oil sands brought

about by the reduction of hydrostatic pressure within them. In part the errors involved in our tests tend to counteract each other, and probably a fair approximation to the real deflections may be obtained by using the test data above discussed. The

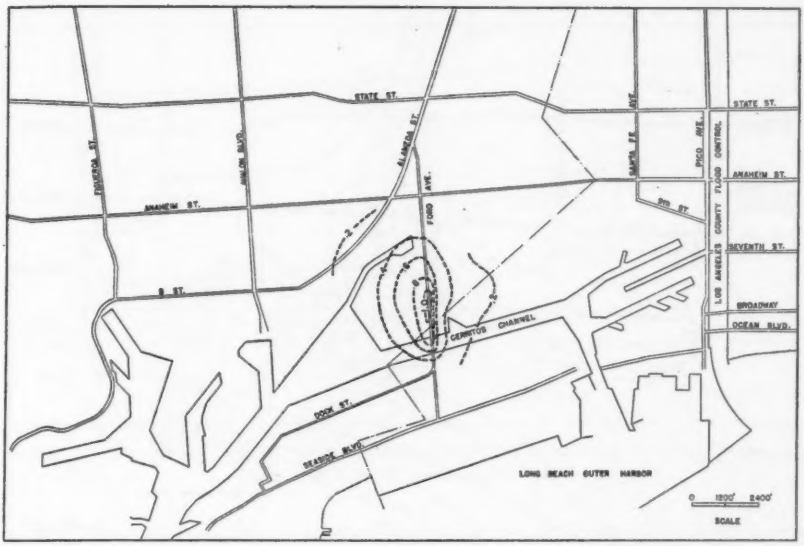


FIGURE 24.—*Theoretical subsidence in the Wilmington oil field to January 1, 1945, due to pressure decline within the "Ford zone" only*

efficacy of the hypothetical mechanism to produce the observed subsidence of the surface is here considered.

For each of the zones, maps were prepared showing the product of "Perforated length" times "Reduction in pressure" for that zone. These were prepared by superposing upon the isopach map of each zone a tracing of the corresponding map showing pressure decline. The product of the two figures at each intersection of contours is readily computed, and with additional interpolations where needed it is a simple matter to construct a contour map showing the product. These contours are of course measures of the proportion of shortening at a given point to that at other points—in order to compute the theoretical shortening in feet it is only necessary to divide the values of the product by the value of the compression modulus for the given zone. Figure 24 shows the resulting contour map for the "Ford" zone, in which the theoretical subsidence of the surface is shown in feet, on the assumptions that the compression modulus = 458,300 p.s.i., the perforated lengths shown in Figure 20 correspond to the thickness of oil sand undergoing pressure decline, and the pressure decline at various points is that given in Figure 17.

Figure 25 was constructed in the same way for the "Terminal zone", based on Figure 21, for thickness of affected section, Figure 18 for pressure decline, and a com-

pression modulus of 166,000 p.s.i. (the average of the four determinations on cores from this zone).

Figure 26 presents similar data for the Tar-Ranger zone, with the fundamental data of Figures 22 for thickness, 19 for pressure decline, and an assumed modulus of

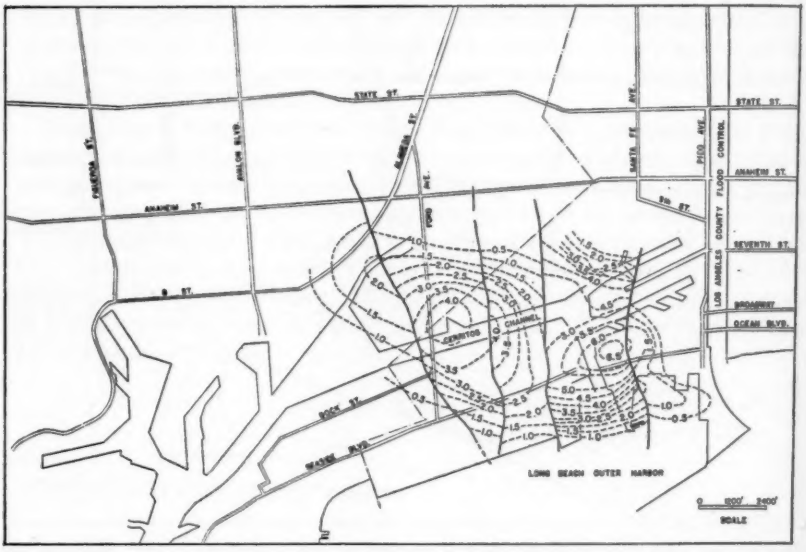


FIGURE 25.—*Theoretical subsidence in the Wilmington oil field to January 1, 1945, due to pressure decline in the "Terminal zone" only*

146,000 p.s.i. (The very low value yielded by UP 223 core was discarded as probably not representative.)

Figure 27 has been prepared from the figures showing the theoretical subsidence for each of the individual zones by superposing one map on the other and adding the contours, as in the construction of an ordinary isopach map. This chart shows that the maximum theoretical subsidence in the oil field should be, on the above postulates, in Block IV, more than 9 feet, with a secondary maximum in Block III amounting to about 7 feet. Disregarding for the moment the excess subsidence that our postulates imply, it appears highly significant that the maximum subsidence deduced from the above data on an assumption equivalent to that of purely elastic response to the increased load due to pressure decline in the oil sands coincides precisely with the area of actual maximum subsidence as revealed by the level data summarized on Figures 6 and 7. There is, it is true, no level data to demonstrate the reality of a secondary maximum in Block III separated from the one in Block IV by a ridge of less subsidence, but the elongation of the depressed area as deduced from the theory here proposed coincides precisely with the known elongation of the area of subsidence. This coincidence puts the burden of proof on one who denies the causal relation be-

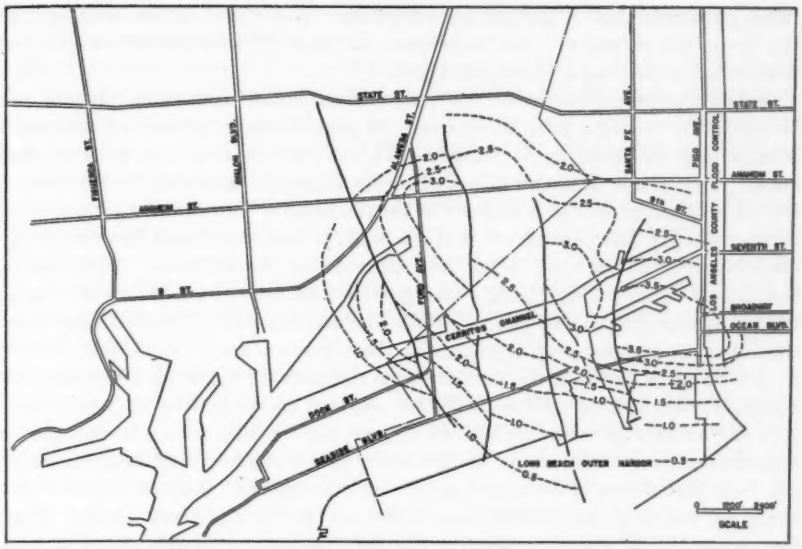


FIGURE 26.—*Theoretical subsidence in the Wilmington oil field to January 1, 1945, due to pressure decline within the "Tar-Ranger zone" only*

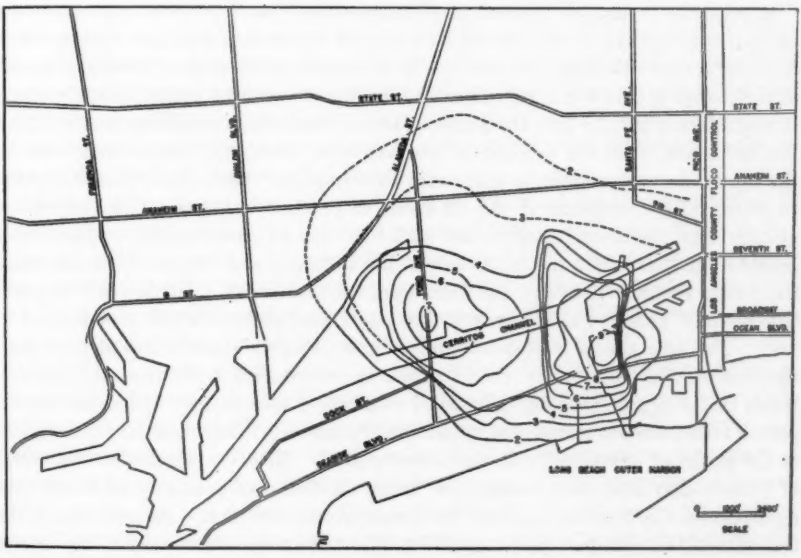


FIGURE 27.—*Total theoretical subsidence in the Wilmington oil field due to pressure decline in all the zones to January 1, 1945*

tween pressure decline in the field and subsidence. Note the correspondence between the theoretical isobase of 2-foot subsidence on Figure 27 and the isobase of 1 foot determined by leveling as shown on Figure 7.

Several features of this line of reasoning demand further discussion. It may well be asked why the subsidence has not been as great as the theoretical amount but is roughly only half that, up to January 1945, the date for which our pressure data apply. Part of the reason has already been mentioned in discussing the thickness of the zones of perforation as a measure of the thickness of strata affected by pressure decline, where it was pointed out that the pressure decline probably has not yet appreciably affected the intervening shale beds within the oil zones. Furthermore, the lines of equal pressure decline of Figures 17, 18, and 19 are of necessity based upon measurements at well points. Both common sense and hydrodynamic theory show that the pressure drop is greatest at these points or the oil would not continue to flow to them and that the pressure drop diminishes away from the wells. Accordingly, the pressure decline curves are maximal curves and by no means represent the average pressure decline throughout the oil sand. On the average the pressure decline over the area of the producing part of the field must be considerably less than that shown in the charts, so it would be expected that the actual decline would be less than that derived from theory on the basis of these figures. These factors combine to make it reasonable that the "theoretical subsidence due to pressure decline" should be greater than that found in the field, without in any way weakening the evidence for the cause-and-effect relation between decline in pressure and subsidence.

It might be argued (in rebuttal to our contention) that the theoretical subsidence computed according to the assumptions recited above should proceed concurrently with the pressure decline, and that this is obviously not the case. Complete records of the change of pressure with time are not available, but from general considerations it is practically certain that the pressure decline has been diminishing in rate during the last years, while the subsidence rate has been increasing. Accordingly, not all the subsidence can possibly be due, as the oversimplified theory just outlined implies, to purely elastic response of the oil sands to pressure changes. This matter has already been discussed in connection with the tests on cores, and it has there been pointed out that under the conditions of the testing it was impossible to segregate the purely elastic response of the cores from the plastic one. Hence the "compression moduli" assumed above are not true elastic moduli but include an error due to flow. The true elastic moduli are greater and probably considerably greater than the ones used in the calculations. Increase in compression modulus would be translated, in the figures showing theoretical subsidence, into smaller figures for the expected instantaneous subsidence on decline of pressure. This error thus contributes to the excess of theoretical subsidence over actual. However, the higher the values of compression modulus assumed, the larger the factor of plasticity that has been incorporated (by implication) into the computations used here. Accordingly, if the test data can be extrapolated to the field at all—and we see no reason why they cannot —we must expect plastic deformation to proceed concurrently with the pressure decline and to continue and even to increase with time. All the curves show this property, and it almost certainly accounts for the speeding up of the subsidence within

recent months at a rate greater than the concurrent pressure decline, contrary to the simplified assumptions used above.

MECHANICAL EFFECTS ON WELLS OF COMPRESSION OF SANDS: Figure 28 illustrates the casing programs of many of the wells in the Wilmington oil field. It shows examples of wells producing from one, two, and three zones. The question arises: If compression of the oil sands caused the subsidence at Wilmington should it not be indicated by mechanical failure of the wells?

In 1941 the ground around the casing of certain wells subsided and broke the concrete mats and foundations at the time that large amounts of water were being pumped from shallow sands near the Graving Dock on Terminal Island. This damage can be attributed to the subsidence following compression of the sands in those shallow aquifers which lie mostly above the shoes of the surface strings of the affected wells.

Compression of deep sands would, however, not be evidenced by such surface effects, at least in wells producing from the highest zone, for the water strings are tied into the casing head at the surface and are cemented to the formations just above the oil sands. At Wilmington the shallowest productive zone lies more than 2300 feet below the surface. Thus, if the oil sands were compressed, the formations between the bottom of the surface string and the oil sands should move downward as a unit and hence would have no effect upon water strings at the surface.

In wells producing from lower zones and from more than one zone, however, there should be some differential movement of casing and the adjacent formations. In any single well such differential movement should increase upward. One should thus expect mechanical failures of the deeper wells, especially in the area of most rapid subsidence. In peripheral areas, one might assume that the smaller differential movement may be taken up by reversal of the normal hanging tension of the casing, by slight curvature of casing, slip of packers, etc. However, where the subsidence is proceeding at a rate of as much as 6 inches a year, one would certainly expect mechanical evidence of the process if, as we believe, the subsidence is due to vertical shortening of the several oil sands.

This has indeed been found in several wells on Terminal Island. As much as 18 inches of casing has had to be cut off, because of protrusion, in a well less than 3 years old. We are not able to assert that every well is so affected—and of course it is possible to explain the ones that are not by postulating movement at the lower end rather than the surface—but the fact that several do show this phenomenon seems to us to corroborate our theory to account for the subsidence.

EVIDENCE FROM ELECTRIC LOGS: In attempting to develop a direct method of determining whether or not the oil zones at Wilmington have undergone compression as the result of loss of hydrostatic pressure, it was thought that, since electric logs had been made for practically all wells in the field, a comparison between those of earlier and later wells might furnish reliable evidence. After considerable investigation, however, it was found that directional surveys of many slant wells were unavailable and that even where wells were known to be practically vertical the distances between them were so great that sand lensing might readily account for any differences in thickness indicated by well logs.

Messrs. Johnson and Cutler examined records from more than 75 redrilled wells

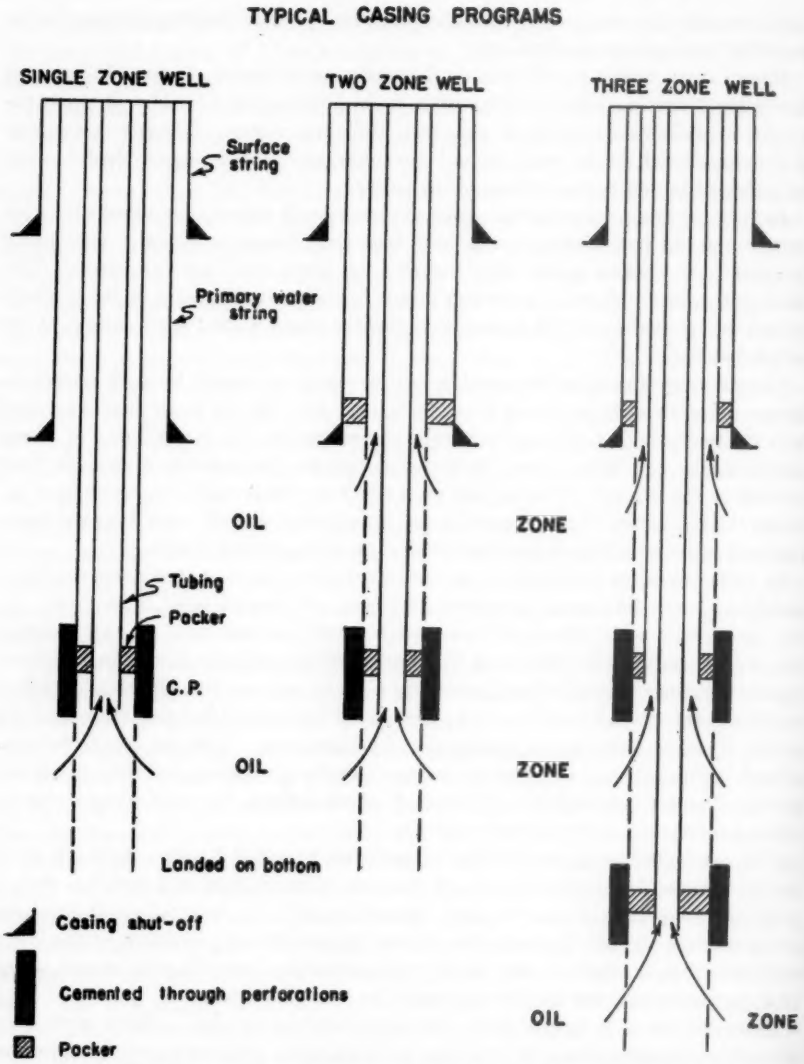


FIGURE 28.—*Representative casing programs employed in the Wilmington oil field*

Based on sketches kindly supplied by Mr. W. W. Cutler

at Wilmington to compare oil-zone thickness. Only 9 wells suitable for the purpose were found. They confined their study to wells for which survey data were accurate, a comparatively long time had intervened between the drilling of the original well and the redrill, the redrill and original well were close together in the zone considered, and sufficient structural information was available for accurate contouring.

It seems unnecessary to discuss these results in detail, as the uncertainties in measuring the depth during electric logging are nearly as great as the differences to be sought. Nine wells hardly furnish an adequate basis for statistical results under these circumstances. For what it is worth, it may, nevertheless, be pointed out that for the 9 wells an average thickness of 430 feet of oil zone shows a shrinkage of $1\frac{1}{3}$ feet in an average time between original drill and redrill of $6\frac{5}{9}$ years. Of these wells, one showed an apparent increase of 3 feet, 2 showed no change, and 6 showed decreases of about 2.5 feet. These results are not given great weight, but so far as they go they conform with expectations on the theory here advanced.

POSSIBLE CONTRIBUTION OF SHALE COMPACTION TO THE SUBSIDENCE: Inasmuch as an excellent case has been made by Tolman and Poland (1940) for the large subsidence in the vicinity of Santa Clara being due to shrinkage of clays as water was withdrawn from them, and the same theory has been applied at Wilmington by Harris and Harlow (1947), it is necessary to consider the possibility that this mechanism may also have been effective in the area here considered.

As outlined by Terzaghi (1943, p. 266–267) the most widely accepted engineering theory of soil consolidation is based on the following assumptions: the voids are completely filled with water, both the water and the mineral grains are incompressible; Darcy's law is strictly valid; the coefficient of permeability is constant; and the time lag of consolidation is due entirely to the low permeability of the soil.

There can be no question that the pore spaces of all the sediments of the Wilmington oil field are water-saturated. The rocks are all marine, and it is highly improbable that those at the depths of the producing horizons have been above sea level since their deposition. The laws of fluid continuity require that no change in pressure can occur within the sediments except by loss of water, so that it is reasonable to accept as a first approximation the postulate that both the water and the mineral grains are incompressible. Even in the sandstones of the oil field, the grain size is such as to make the pore spaces too small to permit turbulent flow, hence Darcy's law should hold both in them and all the more certainly in the associated shales. Insofar as consolidation does occur, there should be a decrease in the permeability of the shale as dewatering progresses within them, as the loss of interstitial water permits consolidation and consequent decrease in size of pore spaces. This must be a very slow process, for the wells are all gun-perforated in the sand zones; and very little shale has direct access to the wells so that the water can escape from it along the bedding planes. The permeability of shale transverse to bedding is very low.

The low permeability of shales transverse to bedding is locally shown by:

(1) the presence of gas caps whose pressure is appropriate to the hydrostatic pressure, and which are slowly growing as the oil extraction continues;

(2) the occurrence of water sands intercalated between the oil sands, especially within the Terminal zone;

(3) the pressure differences between portions of the same stratum separated by a fault;

(4) the distinct differences in gravity of oil from adjacent sands;

(5) the very steep pressure gradients (*see* Figures 17, 18, and 19) in the sandstones, which certainly imply still less regular pressure distribution in the shale interbeds;

(6) the differing chemical compositions of the edgewaters in the several fault blocks.

Accordingly, one would expect such compaction of shale as has taken place in the field to lag considerably behind the compaction of the sandstones. The prompt subsidence of the surface, which became perceptible within a year of the beginning of oil-field operations, argues against the idea that it is due to compaction of shale. A very much stronger argument, however, is that derived from the figures on water extraction.

If compaction of the shale can take place only by loss of fluid from the pore spaces, the water extraction from the field should give a maximum figure for such loss. Both electric logs and coring show that the oil at Wilmington is all in the sandstones. Some of the sandstones, especially in the Terminal zone, contain water, so at least some of the water produced from the oil field was derived from these. To assume that all the water produced came from the shales is therefore heavily to favor the hypothesis of shale compaction.

Through the courtesy of the Long Beach Harbor Department, we have obtained the figures on production of water from the oil field (Blocks III, IV, and V) from the discovery to January 1, 1945.

	Block III	Block IV	Block V
Water production			
(barrels)	202,642	6,305,140	2,675,443
(cubic feet)	1,134,800	35,308,000	14,982,500
Ratio water/oil volume produced	.011	.08	.16
Volume subsidence to 1945 (Vickers)			
(cubic feet)	114,670,000	101,923,000	103,322,000
Ratio water volume to subsidence	.0098	.346	.145

Thus even if all the water produced from the oil field during the course of oil extraction is assumed to have come from the shale beds in the producing zones (and some of it is known to have come from interbedded water sands), the volume produced is wholly inadequate to explain the subsidence through a mechanism of shale compaction. There is no discernible correlation between the subsidence in a given block and the water produced from it.

This is not to deny that there has been some loss of water from the shales to the adjacent sandstones as the pressure fell within them because of oil production. This loss of water must, however, have been very slight and can have contributed but slightly to the total compaction of the oil zones.

Ultimate Subsidence to be Expected: The total production of the Wilmington field for all zones up to January 1, 1945, is estimated to have been about 40 per cent of the oil ultimately recoverable from the oil zones then known. (A new deeper zone, the "237 zone", has since been discovered and may be expected to contribute further to the subsidence.) In general, average bottom-hole pressures of an oil field vary inversely as the cumulative production. Thus in the Wilmington oil field, where the original pressures averaged about 1490 pounds per square inch, the pressure on January 1, 1945, may be estimated to have averaged in all zones about

895 pounds per square inch, an estimate roughly substantiated by the pressures of the wells as recorded on or about that date. This is an average decline of about 40 per cent of the original pressure.

Although, as already mentioned, certain interbedded wet oil sands in the Terminal zone act as water channels from edgewater into the pool and will eventually carry water to even the highest structural locations, nevertheless in the other sands there is no marked edgewater drive, and the pressures in the oil zones may be expected to decrease until the stripper stage of the wells is reached.

The maximum subsidence at Wilmington up to January 1, 1945, was about 4 feet. If subsidence is mainly due to withdrawal of oil and gas with resulting decrease of pressure, it does not follow that, in the future, the rate of subsidence will bear the same relation to oil and gas withdrawal as in the past. Rather it would seem that eventually the rate of subsidence as compared to oil withdrawals will be slower, as it is probable that sands already partially compressed will respond less and less to further loss of pressure in the future.

If, as appears nearly certain, subsidence has been due to oil and gas withdrawals, and that about 40 per cent of the ultimate pressure decline has resulted in a 4-foot subsidence, it seems reasonable to estimate that the ultimate subsidence at Wilmington may amount to as much as 10 feet. Insofar as the pressure decline is offset by edgewater encroachment or diminished by cessation of operations because of economic factors before the bottom-hole pressures become low, the ultimate subsidence may be less. On the other hand, should shale compaction, which we do not believe has yet contributed importantly to the subsidence, really become considerable, the ultimate subsidence may be somewhat greater than the 10 feet estimated. The rate of subsidence will be governed in some degree by the rate of oil and gas production.

Consideration of the stress-strain curves for the sandstone cores tested shows that permanent deformation—flowage—occurs in every core at stresses well within the inferred limit of 2000 p.s.i. which may be expected in the deepest zones in the field. Because of the uncertain influence of time on the flow of the rocks no laboratory data collected in this investigation can be extrapolated to the field with sufficient confidence to justify an estimate of the ultimate plastic deformation to be expected within the oil sands. As noted in an earlier paragraph, the mechanism of flow must be one of grain readjustment and squeezing of cement into the voids of the sandstones, for the mechanical properties of the sand grains are such as to make their fracture or flowage highly improbable under the operating stresses. The porosity of the sandstones ranges between 24 and 36 per cent. The percentage of cement—chiefly calcite—is probably not very high but is greater in sandstones of low porosity than in those of high. The stresses operating in the rocks are statistically nearly uniform, but such an inhomogeneous aggregate must fail to transmit the stress trajectories like a metal or other essentially continuous mass. The stress concentration on points of contact of individual grains must, even at modest statistical pressures, be very high and sufficient to cause flowage of the cement from places of high stress into the stress shadows between the grains. Rough computations of density of the test

cores prior to and after testing shows a reduction in porosity that generally increases with the amount of permanent deformation brought about in the specimen during the test. The accuracy of the porosity measurements was not sufficient to justify other than a qualitative discussion of their significance. However, the decrease is shown by every specimen tested and must be interpreted as due to the mechanism just suggested—*i.e.*, to flowage of the cement from points of contact or potential contact of the component grains into the protected voids between them. Filling of the voids would cause an increase in the friction of flow, and this increase must become very high long before the last of the pore space is filled. For any possible pressure in the oil field, flowage should become vanishingly small while there is still a considerable pore space in the rocks.

So it appears that the response of the sandstones in the oil field to increased load may be divided into three phases: (1) the purely elastic and instantaneous shortening that must occur simultaneously with the change in pressure; (2) a phase in which flow of the inter-granular cement begins, slowly at first because the threshold stress required to induce it is only slightly exceeded, but increasing in rate as the stress builds up; and (3) a phase when the increasing friction of flow owing to filling of the pore spaces slows down the flowage and finally stops it. There are no quantitative data available with which to evaluate accurately the results to be expected at Long Beach. An estimate of the extent of pressure drop compared with that ultimately to be expected shows that about 40 per cent of the ultimate stress has already been added to the oil sands. The purely elastic response to this pressure increase has already occurred. Although the figures suggested in the preceding section have been computed on the assumption that the deformation has been wholly elastic, it was pointed out that this assumption was a convenient one only, and that the stress-strain curves used in working it out actually include a considerable plastic factor. For this reason, among others, the theoretical maximum subsidence comes out about twice as great as the actual, which is known to involve flow as well as elastic shortening. Although the flow may be expected to continue as the stress increases, it will probably do so at a diminishing rate, and it seems likely that, although the stress increase now is only about 40 per cent of the ultimate (assuming the oil production continues to the exhaustion of the field), somewhat more than 40 per cent of the ultimate sandstone compaction has already occurred.

Another factor which may increase the ultimate subsidence beyond this estimate is the loss of water from the interbedded shales, as the pressure in the sands drops. Although this process has probably not yet been significant, it may be expected to increase with time. Owing to the impermeability of the shales, significant shrinkage would require considerable time. It would probably take place so slowly that, although there is little sign of water-drive in the field the recharge of the sandstones with water from outside the productive area may essentially counterbalance it. We have therefore regarded this factor as negligible, though under other conditions it has been a large factor in subsidence. On the other hand, the pressure decline within the field will tend to equalize, so that portions now lagging in subsidence behind the most active areas will gradually tend to overtake them. This is notable in particular on Block III of the oil field which has lagged in development.

OTHER EXAMPLES OF SUBSIDING OIL FIELDS

If the rapid subsidence of the Long Beach Harbor area is largely due to oil-field operations, it is of interest to examine other areas of subsidence in oil fields. Published reports on oil-field subsidence may be scarce because of the special conditions needed for the discovery of the phenomenon. Coastal fields or those along lakes are the only ones likely to show subsidence sufficiently marked to arouse comment. A subsidence of even as much as 5 feet per mile would be likely to pass unnoticed in an inland field unless it were crossed by precise level lines. Furthermore, unless the spirit leveling is repeated any subsidence may go undetected.

The rapid subsidence of the Goose Creek oil field on the shore of San Jacinto Bay in Harris County, Texas, has elicited much interest from geologists (Minor, 1925; Pratt and Johnson, 1926; Snider, 1927; Sellards, 1930). Minor (1925) pointed out that since the active development of Goose Creek in 1916 there had been a marked subsidence of the area over the center of the field. A land area, formerly ½ to 2 feet above mean tide was submerged under possibly 3 feet of water. In many places, along the north and south limits of the field, miniature faults were traced for considerable distances. Elevations, compared with those determined by the U. S. Geological Survey in 1916, showed the greatest subsidence over the area of greatest production, with the surrounding area gradually resuming its original elevation a short distance beyond the oil-field limits.

Minor's explanation for this subsidence was that the movement of the gas, oil, and water in the sands caused readjustment and closer packing of the sand grains. The overlying comparatively weak clays, shales, and sands gave way and settled to a lower position because of the readjustment of the underlying sands.

Pratt and Johnson (1926) published a more detailed paper on the Goose Creek subsidence, with an isobase map showing the close correlation of the productive area with the subsidence contours. They concluded that extraction of oil, water, gas, and sand from beneath the affected area caused the subsidence because the subsidence was purely local and corresponded closely with the area of extraction, the time of the subsidence corresponded with the time of extraction, and because continued extraction is accompanied by continuing subsidence.

The subsurface conditions in the Goose Creek field are not entirely similar to those of the Wilmington field. At Goose Creek the oil sands are discontinuous lenses surrounded by relatively impermeable clays which inhibit free flow of fluids. However, water may slowly drain from the clays into the sands, causing consolidation of the clays and thinning of the sequence of beds, as it probably does to a smaller extent in the Wilmington field. In the Wilmington field the oil sands are more continuous, although broken by faults, some of which have limited fluid flow between blocks.

Another dissimilarity is that there was a considerable waste of gas pressure in the early development of the Goose Creek field and perhaps more sand production than in the Wilmington field. At Goose Creek the original reservoir pressure of 1000 to 12000 pounds per square inch has been reduced to atmospheric pressure. This is a greater average decline in subsurface hydrostatic pressure than in the Wilmington field to the present date. Regardless of the dissimilarities in details, the subsidences

in these two fields are to a considerable extent parallel phenomena and can hardly be considered fortuitous.

The reported subsidence of 1 to 2 feet per year in the oil fields at Lake Maracaibo, Venezuela (Kugler, 1933) is similar to the Goose Creek subsidence in that considerable oil has been produced in both areas and that the subsidence quickly became apparent owing to the transgression of bodies of water over the land.

The subsidence of the Huntington Beach oil field is another example. Although the data on level changes near Huntington Beach are neither so numerous nor so well distributed areally as those for the Long Beach Harbor area, third-order levels by Piper and Phelps of the U. S. Geological Survey in 1941 indicate greater subsidence in the area of the Huntington Beach oil field than has occurred up or down the coast from that field, during the interval 1932–1941. The 1941 levels were referred to Tidal 8 B.M., the 1932 levels to the U. S. Coast and Geodetic Survey Preliminary Adjustment of 1928. Bench marks along the Coastal Highway 1.2 miles southeast of Huntington Beach and between Sunset Beach and Bolsa Bay subsided, in this interval, .094 and 0.285 foot respectively, while a bench mark at the intersection of 17th Street and Coast Highway in Huntington Beach and one at a point 1.8 miles northwest of Huntington Beach subsided 1.07 and 1.18 feet, respectively. A fifth bench mark, 2.5 miles northwest of Huntington Beach, subsided .85 foot. Thus maximum subsidence occurred along the stretch of highway within the Huntington Beach oil field.

Another example of oil-field subsidence is the Long Beach oil field centering near Signal Hill (Grant, 1944). An isobase map showing differential subsidence of this area between 1925 and 1930 was prepared by Captain Burt Harmon for the City of Long Beach Water Department; the maximum subsidence was more than 0.4 foot. The isobases show a definite correlation with the outline of the productive area of the field in 1928, the maximum subsidence being in approximately the center of the productive area of that time. Also, there is considerable parallelism between the isobases and the structural contours on the top of the Brown zone (Stolz, 1943). In the Long Beach field the producing horizons extend to more than 7000 feet below the surface, and pressures in some of the wells appear to have declined by as much as 1000 pounds per square inch or more. While the total subsidence in the Long Beach field from its discovery to the present is unknown to us the rate for the period covered by Mr. Harmon's map is considerably less than the rate of subsidence in the Wilmington oil field. Tectonic movements seem to be much more active in the Signal Hill area than in the harbor area and may confuse the local picture more. Furthermore, the spirit-leveling data available to us is much less adequate so that a close parallelism in determination of subsidence can hardly be expected.

Repeated spirit leveling along the coast of Santa Monica Bay has revealed subsidence in the area of the Playa del Rey oil field (Grant and Sheppard, 1939). The highest rate determined between 1925 and 1937 was over 0.07 foot per year and occurred at the bench mark at the intersection of 42nd Avenue and Trollyway, City of Venice. This is near the anticlinal axis in the oil field. The subsiding area includes part of the Del Rey Hills, at least as far east as Lincoln Avenue, so that rocks older than the valley fill in the Ballona Plain are included. The history of bottom-hole pressures in the oil wells is not available to us, but the general structure and

stratigraphy of the Playa del Rey oil field have been described by Metzer (1943).

No data on subsidence of the Inglewood oil field have been published, but subsidence was recognized in the Baldwin Hills (Hayes, 1943). Between 1934 and 1943 the maximum surveyed subsidence was 0.39 foot at a bench mark a little over a mile north of the intersection of Slauson and La Brea avenues. This is near the structural high of the Vickers-Machado zone (Driver, 1943). The decrease in bottom-hole pressures in this field is unknown to us. The Newport-Inglewood fault zone transects this field, and tectonic movements are believed to be active there. According to Hayes' report, uplift has occurred at a number of bench marks between Manchester and Slauson avenues. Therefore, the vertical movements in the Baldwin Hills-Inglewood area are probably complicated by a combination of tectonic forces and subsidence due to oil-field operations.

Subsidence in the Santa Fe Springs oil field has been known among oil company employees for a number of years. The only quantitative data available to us are those from level surveys made by the County Road Department of the Los Angeles County Surveyor's Office. Differences in elevation of bench marks along Anaheim-Telegraph Road and along Norwalk Boulevard between surveys of 1927 and 1932 show that the maximum recorded subsidence, amounting to 0.93 foot during the 5-year interval occurred near the intersection of Anaheim-Telegraph Road and Norwalk Boulevard. This is close to the center of the producing area of the field. The total subsidence to date is unquestionably considerably greater than that recorded by the surveys mentioned above as the field has been producing large quantities of oil since 1921, and the surveys cover only 5 years of a total productive history of about 24 years. The oil is produced from eight zones ranging through more than 4000 feet of depth. The decrease of bottom hole pressures has no doubt been substantial, but figures have not been available to us. The structural conditions are similar to those in the Wilmington field.

In our opinion the known subsidence of several oil fields during their development represents a cause and effect phenomenon. More examples no doubt would have become known had there been adequate leveling data and more interest in the subject.

ADDENDUM

This study takes account only of data prior to January 1945 and was completed during 1946. Since that time two additional oil zones, the "237" zone and the "Union Pacific" zone have been developed. Our estimate of the ultimate subsidence to be expected must, of course, be corrected because of these new factors. A preliminary study of the new data indicates that not less than 4 feet should be added to the estimate of 10 feet (ultimate subsidence) given in this paper. The maximum subsidence at this time is about 8 feet. November 19, 1948.

REFERENCES CITED

Benioff, Hugo (1938) *The determination of the extent of faulting, with applications to the Long Beach earthquake*, Seismol. Soc. Am., Bull., vol. 28, p. 77–84.

Bowlus, Fred D. (1943) *Elevation changes along the line of the outfall sewer from the Joint Disposal Plant to White Point*, unpublished report addressed to A. M. Rawn, Chief Engineer, Los Angeles County Sanitation Districts.

Byerly, Perry (1942) *Seismology*, Prentice-Hall, New York.

Crown, Walter J. (1942) *Wilmington oil field*, Calif. Dept. Nat. Resources, Div. Oil and Gas, Summ. Operations, vol. 26, July 1940–June 1941, p. 5–11.

Driver, Herschel (1938) *Inglewood oil field*, Unpublished Master of Science Thesis, Univ. S. Calif.

——— (1943) *Inglewood oil field*, Calif. Dept. Nat. Resources, Div. Mines, Bull. 118, p. 306–309 especially Fig. 128.

Eaton, J. E. (1923) *Structure of Los Angeles Basin and environs*, Oil Age, vol. 20, p. 8–9, 52.

——— (1924) *Structure of Los Angeles Basin and environs*, Oil Age, vol. 21, p. 16–18, 52, 54.

——— (1926a) *Stratigraphy and structure of Los Angeles Basin described*, Oil and Gas Jour., vol. 24, p. 84, 101, 104, 106.

——— (1926b) *A contribution to the geology of the Los Angeles Basin*, Am. Assoc. Petrol. Geol., Bull., vol. 10, p. 753–767.

——— (1933) *Long Beach, California, Earthquake of March 10, 1933*, Am. Assoc. Petrol. Geol. Bull., vol. 17, p. 732–738.

Eckis, Rollin (1934) *Geology and ground water storage capacity of valley fill*, Calif. Div. Water Resources, Bull. 45.

Ferguson, R. N., and Willis, C. G. (1934) *Dynamics of oil field structures in Southern California* Am. Assoc. Petrol. Geol., Bull., vol. 8, p. 576–583.

Grant, U. S. (1939) *Preliminary report on a geological investigation of the Long Beach Tidelands*. Unpublished report to the Long Beach Harbor Department.

——— (1941) *Report on areal subsidence of Terminal Island, Long Beach, California, during July, August and September, 1941*, Unpublished report to the Board of Harbor Commissioners, Long Beach, California, dated August 14 and September 22.

——— (1944) *Subsidence and elevation in the Los Angeles region*, Science in the University, p. 148–149, Univ. Calif. Press, Berkeley and Los Angeles.

——— and Sheppard, W. E. (1939) *Some recent changes of elevation in the Los Angeles Basin of southern California and their possible significance*, Seismol. Soc. Am., Bull., vol. 29, p. 299–326.

Gutenberg, Beno (1934a) *Das Seismological Laboratory in Pasadena*, Ergebnisse der Kosmischen Physik, Bd. 2, p. 236.

——— (1934b) *Gerlands Beiträge Geophysik*, Bd. 41, p. 114–115.

——— (1941) *Mechanism of faulting in southern California indicating by seismograms*, Seismol. Soc. Am., Bull., vol. 31, p. 300.

Harris, Frederick R., and Harlow, Eugene H. (1947) *Subsidence of the Terminal Island-Long Beach area, Calif.*, Am. Soc. Civil Eng., Pr., vol. 73, p. 1197–1218.

Hayes, Stephen A. (1943) *Report on earth movement measurements in the Baldwin Hills and Inglewood areas*, Unpublished report, Los Angeles County Surveyor's Office, October 29.

Jacob, C. E. (1940) *On the flow of water in an elastic artesian aquifer*, Am. Geophys. Union, Tr., pt. 2, p. 574–586.

Jensen, Joseph (1928) *Development in southern California since 1923*, Am. Assoc. Petrol. Geol., Bull., p. 625–650.

——— and Robertson, Glenn D. (1928) *Developments in Southern California*, Oil and Gas Jour., vol. 26, p. 152–154.

Krynine, D. P. (1941) *Soil mechanics*, McGraw-Hill Book Co., New York.

Kugler, H. G. (1933) *Contribution to the knowledge of sedimentary volcanism in Trinidad*, Inst. Petrol. Technol., Jour., vol. 19, p. 743–760. Discussion by M. ap Rhys, p. 769–770.

Meinzer, O. E., Wenzel, L. K., and others (1944) *Water levels and artesian pressure in observation wells in the United States in 1942*, U. S. Geol. Survey, W. S. Paper 949.

Mendenhall, W. C. (1904) *Development of underground waters in the central coastal plain of southern California*, U. S. Geol. Survey, W. S. paper 138.

Metzer, Loyde H. (1943) *Playa del Rey oil field*, Calif. Dept. Nat. Resources, Div. Mines, Bull. 118, p. 292–294.

Minor, H. E. (1925) *Goose Creek oil field, Harris Co. Texas*, Am. Assoc. Petrol. Geol., Bull., vol. 9, p. 286–297.

Nicholson, G. L. (1929) *Variations in levels, 1919 to 1927, in Los Angeles Harbor*, Seismol. Soc. Am., Bull., vol. 19, p. 200–205.

Piper, A. M., Poland, J. F., and others (1943) *Progress report on the cooperative ground-water investigation in the Long Beach-Santa Ana area, California*, U. S. Geol. Survey, Unpublished records, subject to revision, in open files, Long Beach.

Poland, J. F., and others (1942) *Descriptions of water wells in the coastal zone of the Long Beach-Santa Ana area, California*, U. S. Geol. Survey, Unpublished records, subject to revision, December.

———, Piper, A. M., and others (1945) *Geologic features of the coastal zone of the Long Beach-Santa Ana area, California, with particular respect to ground-water conditions*, U. S. Geol. Survey, Unpublished records, subject to revision, May.

Pratt, W. E., and Johnson, D. W. (1926) *Local subsidence of the Goose Creek field*, Jour. Geol., vol. 34, p. 577–590.

Reagan, J. W. (1910) *Report upon the control of flood waters*, Los Angeles County Flood Control District, report filed January.

Reed, Ralph D., and Hollister, J. S. (1936) *Structural evolution of Southern California*, Am. Assoc. Petrol. Geol., Bull., vol. 20, p. 1671–1679.

Sellards, E. H. (1930) *Subsidence in Gulf Coastal Plains salt domes*, Univ. Texas, Bull. 3001, p. 9–36.

Snider, L. C. (1927) *A suggested explanation for the surface subsidence in the Goose Creek oil and gas field*, Am. Assoc. Petrol. Geol., Bull., vol. 11, p. 729–745.

Stolz, Harry P. (1943) *Long Beach oil field*, Calif. Dept. Nat. Resources, Div. Mines, Bull. 118, p. 321, Fig. 133.

Terzaghi, Karl (1938) *Settlement of structures in Europe and methods of observation*, Am. Soc. Civil Eng., Tr., vol. 103, p. 1436.

——— (1943) *Theoretical soil mechanics*, John Wiley & Sons, N. Y., p. 266–267.

Tolman, C. F., and Poland, J. F. (1940) *Groundwater, salt-water infiltration, and ground recession in the Santa Clara Valley, Santa Clara County, California*, Am. Geophys. Union, Tr., pt 1, p. 23–34.

Tsuboi, C. (1939) *Deformations of the Earth's crust as disclosed by geodetic measurements*, Ergebnisse der kosmischen Physik, Bd. 4, p. 117–120.

U. S. Coast and Geodetic Survey (1941) *First order leveling, Long Beach area, Calif.*, Photolithographic pamphlet, dated May 20.

——— (1943?) *Releveling vicinity of San Pedro, Wilmington and Long Beach, Calif.*, Photolithographic pamphlet dated Sept. 14, 1942, with note referring to the adjustment, dated Feb. 5, 1943.

——— (1945) Mimeographed list of unadjusted elevations in the Long Beach-San Pedro area determined during July and August, 1945.

——— (1946) *Preliminary unadjusted field elevations derived from leveling on Terminal Island, Feb. 27–March 6, 1946*, Mimeographed list supplied by courtesy of Roland D. Horne, Supervisor, S. W. District, March 13.

Water Department, City of Long Beach, California (1943–1944) History and Annual Report.

Willis, Bailey, and Wood, H. O. (1922) *Fault map of the State of California*, Seismol. Soc. Am.

Wilmington Field Engineering Committee (1942) Files of Petroleum Administration for War. Detailed structural contour maps, cross sections, and production tables, dated November.

Winterburn, Read (1940) *Effect of faulting on accumulation and drainage of oil and gas in the Wilmington oil field*, Am. Inst. Min. Metall. Eng., Tech. Pub. 1154.

——— (1943) *Wilmington oil field*, Calif. Dept. Nat. Resources, Div. Mines, Bull. 118, p. 301–305.

Wissler, Stanley G. (1943) *Stratigraphic formations of the producing zones of the Los Angeles Basin oil fields*, Calif. Dept. Nat. Resources, Div. Mines, Bull. 118, p. 209–234.

Wood, H. O. (1933) *Preliminary report on the Long Beach Earthquake*, Seismol. Soc. Am., Bull., vol 23, p. 43–56.

Woodring, W. P., Bramlette, M. N., and Kew, W. S. W. (1946) *Geology and paleontology of Palos Verdes Hills, California*, U. S. Geol. Survey, Prof. Paper 207.

———, Stewart, R. B., and Richards, R. W. (1940) *Geology of the Kettleman Hills oil field, California*, U. S. Geol. Survey, Prof. Paper 195, p. 152–153.

UNIVERSITY OF CALIFORNIA, LOS ANGELES, CALIF.

MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, NOVEMBER 14, 1947.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 60, PP. 531-560, 5 FIGS., 1 PL. MARCH 1949

FURTHER STUDIES IN BIOGEOCHEMISTRY

BY HARRY V. WARREN AND ROBERT E. DELAVAULT

CONTENTS

	Page
Abstract	532
Introduction	532
Acknowledgments	533
Chemical methods suitable for biogeochemical prospecting	533
Problem outlined	533
Copper	535
Electro deposition and microtitration	535
Dithizone extraction	537
Dithizone titration with "mixed color end point"	538
Procedure	539
Zinc	539
Ferrocyanide	539
Dithizone methods	540
Sampling	540
General	540
Collection of samples	541
Preparation of samples for analyses	543
Selection of areas	543
Studies of individual areas	543
Sullivan (Kimberley) area	543
General	543
Climate	544
General geology	544
Sampling	544
Copper and zinc	545
Boron content of some trees	545
Manganese in samples from the Sullivan area	545
Comparison with previous results	548
Britannia Mine area	550
General	550
Climate	550
General geology	550
Fairview suite	552
Copper plant suite	552
Comparison with previous results	553
Conclusions	553
References cited	555
Appendix	556

ILLUSTRATIONS

Figure	Page
1. Sketch showing filtering apparatus	536
2. Sketches showing electrolytic apparatus	536

Figure Page
3. Sketch of cathodic and anodic wires in the electrolytic apparatus..... 536
4. Map of the Fairview Mine, Britannia Beach, B. C..... 551
5. Map of the Copper Plant, Britannia Beach, B. C..... 552
Plate Facing page
1. Map of the Sullivan Mine, Kimberley, B. C..... 558

ABSTRACT

Although previous work indicated that there may exist a striking relationship between the mineral content of plants and that of the underlying soils and rocks it was thought advisable to re-examine the problem, employing different collectors and analytical methods. Furthermore, if this work were ever to have an economic application, it would be necessary to develop simpler and more direct methods of collecting, sampling, and analyzing.

This paper outlines some of the analytical methods employed and describes a dithizone method which seems eminently suitable for both copper and zinc analyses.

Evidence shows that twigs, rather than leaves or needles or even fruit, are probably more satisfactory as indicators of variations in the metal content of soils and rocks. Twigs are easier to collect, to sample, and to ash; indeed, satisfactory results have been obtained from 1- and 2-gram samples. If the evidence is substantiated it may be possible to carry on biogeochemical prospecting in winter.

Numerous analyses of samples from the Britannia and Sullivan mines are tabulated, and their significance is discussed. The results are compared with those obtained previously.

In some areas the zinc-copper ratios may, in biogeochemical prospecting, be more significant than the absolute amounts of zinc and copper present in the trees and lesser plants, particularly when the absolute amounts of copper and zinc are low.

INTRODUCTION

In recent years the department of Geology and Geography at the University of British Columbia has been investigating the possibility of biogeochemical prospecting in the search for hidden ore bodies. Early results were most encouraging (Warren and Howatson, 1947)—in fact, so satisfactory on paper that they induced a healthy and natural scepticism in some readers. The writers fully appreciated this scepticism and, indeed, shared it. Obviously much more work had to be done before any valid conclusions could be reached and before biogeochemical prospecting could be put to practical use. This paper outlines the work done in checking previous studies and discusses two major problems, those of analyzing and sampling.

H. E. Hawkes (The Geological Survey's Geochemical Prospecting Unit, 1946) said:

> "Our experience so far has indicated very vividly the desirability of getting analytical results on the spot, so that we don't waste time collecting and analyzing material from unpromising areas, also so that we know when we are getting warm, so to speak, and should intensify our efforts."

The authors are in hearty accord with this report, and for this reason a considerable portion of this paper deals with some of the chemical methods which we have investigated and the results obtained.

Sampling practices adopted are perhaps almost as important as the analytical methods. Although thorough investigations have not yet been completed, evidence

indicates that twigs are the most satisfactory parts to sample. Twigs are much easier to collect, ship, and ash, and they seem to fluctuate less in both copper and zinc values than do fruit, needles, or leaves.

Many analyses are given, and some conclusions are drawn.

ACKNOWLEDGMENTS

The authors express deep indebtedness to The Geological Society of America for a grant from the Penrose Bequest. This grant, with one obtained from the Board of Governors of the University of British Columbia through the efforts of Dean Daniel Buchanan, made possible this research. Mr. C. P. Browning, General Manager, Britannia Mining and Smelting Co. Ltd., and Mr. R. W. Diamond, Vice-President and General Manager of the Consolidated Mining and Smelting Co. of Canada Ltd., not only made the path smooth, but freely gave permission to publish the results: to these men and to their many staff members who gave generously of their time, assistance, and advice, the authors wish to express their thanks.

Mr. C. H. Howatson and Miss Ruth Irish assisted in this study: the former in collecting and mapping the samples, the latter in the laboratory. Mr. R. G. McCrossan made the spectrographic analyses of the boron. Many University colleagues assisted by providing equipment and invaluable advice; to them also the authors acknowledge their deep indebtedness.

The authors wish also to thank Messrs. R. E. Stevens, H. W. Lakin, and H. E. Hawkes of the U. S. Geological Survey, and W. O. Robinson of the U. S. Bureau of Plant Industry, who reviewed the manuscript and made many valuable suggestions. Some of these suggestsions have been incorporated in this paper, and others will be considered and, when possible, acted on during our future investigations.

CHEMICAL METHODS SUITABLE FOR BIOGEOCHEMICAL PROSPECTING

PROBLEM OUTLINED

In our early work 100-gram samples permitted both copper and zinc to be determined from the same sample (Warren and Howatson, 1947, p. 808–809).

Although we have checked the results obtained by this method and found them reasonably satisfactory it requires large and bulky samples, the collecting and transporting of which present obvious difficulties. Furthermore, under some circumstances zinc determinations may, by this method, be low.

If biogeochemical prospecting were ever to be undertaken on a commerical scale the samples for analytical work should not exceed 5 grams and should be less if possible.

Throughout this paper,

1 milligram = 1000 γ (gamma);

1 γ per gram = 1 p.p.m. (part per million)

Preliminary investigations show that for conifers and alders significant abnormal amounts of copper and zinc might be said to commence with 12 and 40 p.p.m. respectively of dry plant material; in neutral or alkaline soils much smaller amounts

of these metals may be significant. In one limestone area studied, from 3 to 5 p.p.m. of copper may be indicative of copper concentrations, whereas concentrations of copper of more than 12 p.p.m. and of zinc of more than 40 p.p.m. are known to occur in dry plant material grown in soil containing no excess copper or zinc. However, the leaves and twigs of the trees selected in slightly to moderately acid soils for our particular biogeochemical investigations consistently tended in our so-called "negative" areas to fall between 2 and 12 p.p.m. in copper and 20 and 40 p.p.m. in zinc. Preliminary investigations also showed that in areas in which no copper ore was known to occur the copper content of the dry plant material usually ranged from 2 to 10 p.p.m., the zinc between 20 and 40 p.p.m.

The problem, therefore, was to find an analytical method which would give an accuracy of within 10 per cent or better, where copper and zinc were present in dry material in amounts greater than 12 and 40 p.p.m. respectively. Actually even this degree of accuracy would not be needed for field work where probably an accuracy of within 25 to even 50 per cent would suffice.

The results presented in this paper were obtained from laboratory analyses, but all our methods were developed with a view to their being adaptable to field use. Indeed a small steel muffle, for use in the field, was built and tested. It was possible, by burning chopped wood around this muffle, to heat it to a dull red heat and to ash twigs in less than 1½ hours. The time involved in ashing twigs is considerably less than that needed for ashing milled leaves and twigs.

Analyses made in the field agree well with laboratory results as far as Cu/Zn ratios are concerned. Tolerable discrepancies in p.p.m. of dried plant material—usualy within 25 per cent—result from substituting oven drying for simpler but slower air drying. Once the ashes are obtained no step of the procedure presents any difficulty.

It was our desire to develop a field technique which led to our eschewing spectroscopic methods, in spite of good equipment being available. Indeed, had absolute accuracy rather than relative accuracy combined with field practicability been our goal, we would probably not have adopted dry ashing, which certainly does not appear to produce the best results in trace-metal investigations. Our experience suggested that greater accuracy than this would be unnecessary and would represent wasted effort because sampling cannot be done with greater exactness. Even less-accurate chemical determinations are required with concentrations of less than 12 p.p.m. of copper or 40 p.p.m. of zinc because such low samples have no economic importance. Nevertheless, we attempt to achieve the most accurate results possible as they may have some geological and climatic significance.

The following methods of analysis were investigated:

Copper (1) Electrodeposition and microtitration
(2) Dithizone extraction
(3) Dithizone titration with "mixed color end point"

Zinc (1) Hydrogen sulphide precipitation and microtitration
(2) As for copper but with a different pH
(3) As for copper but with a different pH

The plant material was kept in paper bags to avoid contamination and was air-dried at room temperature (65°F). When dried the material was ground to −40

mesh and ashed in a porcelain evaporating dish at 550°C for several hours, usually 4, or until no charred matter was visible.

In this paper, unless otherwise stated, the copper or zinc is expressed as p.p.m. of dried plant material, a practice commonly accepted.

COPPER

Electro deposition and microtitration.—Since previous work showed that, in general, in our areas, "normal" amounts of copper in a 5-gram sample of dry plant material might be 10 to 50 γ and abnormal amounts from 50 to 5000 γ, it was decided to test a semimicroanalytical method. This method proved particularly suitable for checking the abnormally high copper content of some samples.

Control samples containing 1000 to 100 γ of copper were run in 5 to 7 ml of solution, and it was found that within this range copper determinations could be made within from 1 to 2 per cent accuracy. However, these results were obtained with very simple apparatus.

It follows that, using 5 grams of dried plant material containing a "normal" amount of copper, it was not possible to determine its contents with precision. Nevertheless, a rough indication would be obtained, and a sample classified as showing "no copper visible", "trace", or, with larger amounts, "token analytical results" could be given. However, in practice there is a fair degree of correlation between these "token analytical amounts" and results obtained from the more specific dithizone methods described later. Our experience shows that accuracy within 1 per cent in analytical work is far beyond anything obtainable with ordinary sampling methods.

The ash is first dissolved in 5 N sulphuric acid with a few drops of SO_2 solution added to reduce any manganese present. The excess is evaporated until white fumes no more evolve, and the residual is gently heated with 5 ml of $\frac{N}{2}$ sulphuric acid. The solution which now contains all of the copper and most of the zinc is microfiltrated into a 10-ml beaker. (This can readily be made from the lower end of an 18-mm diameter pyrex test tube, to which is soldered an Emich filtering rod stuffed with asbestos.) (Fig. 1)

However, this method does not completely dissolve the zinc in the plant ash. Hibbard (1934) pointed this out, and our studies confirm his findings. In some cases as much as half the zinc contents were undissolved by the sulphuric acid. If both metals must be estimated it is better to use Hibbard's method, attacking the ash with 2 N·HCl and precipitating by H_2S gas the solution buffered to about pH3. No previous filtering is necessary, and some talc powder is even added to improve the collection of the sulphides. These precipitates are then collected on a paper filter, and the zinc sulphide is dissolved with cold N·HCl acid. The copper, together with any other heavy metals present, is dissolved from the filtrate with 50 per cent HNO_3 and may be electro-deposited later.

All the data obtained for this paper were from a sulphuric-acid solution to which 4 drops of concentrated HNO_3 were added. In spite of slight evaporation, washing

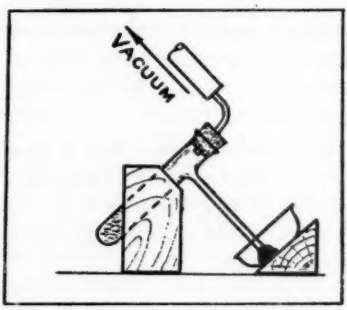


FIGURE 1.—*Filtering apparatus, ½ size*

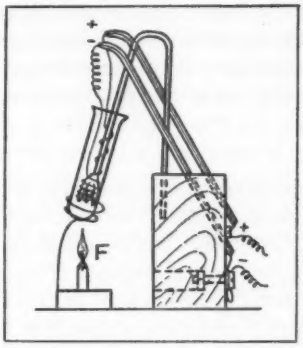


FIGURE 2.—*Electrolytic apparatus, ½ size*

The micro-beaker is held in a pure aluminum wire fixed to the wooden block bearing the micro-flame F.

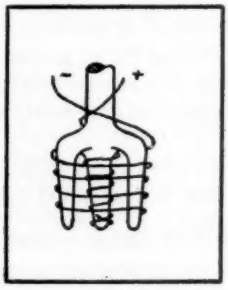


FIG. 3A.

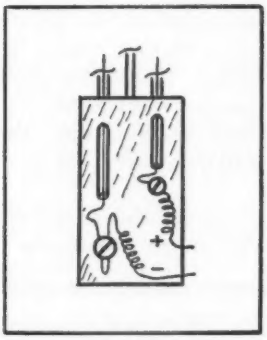


FIG. 3B.

FIGURE 3.—*Cathodic and anodic wires in the electrolytic apparatus, natural size*

The third prong is behind the axis

increased the volume of the solution to about 7 ml containing usually 50 to 1000 γ of copper. This was electrolyzed with .03 ampere for 45 minutes on a simplified electrolytic apparatus made in our laboratory. Figures 2 and 3 illustrate the apparatus used.

Instead of the usual wire-gauze cathode a platinum wire, gauge 28, about 0.3 mm, was used. About 3 inches of this wire was coiled around the exterior prongs of a glass anode holder, the anodic wire being wound around the axis of this holder. The axis or stem and the three-pronged anode holder was tapered to hold the coils in their place (Fig. 3). The cathode was soldered into a glass holder which could slide downward in a wooden block. This made it easy to free the cathode, treat it in a microflask with a few drops of sulpho nitric solution (1 vol. H_2SO_4, 1 vol. HNO_3,

2 vol. H_2O), dissolve the copper, and replace it. The anode was soldered into a similar but fixed glass tube holder. The platinum wires were twisted with wires of pure nickel inside the glass tubes, and nickel wires were used as conductors in the vicinity of the apparatus.

Gentle boiling was sufficient to stir the solution during electrolysis, and no air bubbling through a siphon was necessary. However, polarization of electrodes, which prevents dissolution of copper during washing, is not satisfactory unless these electrodes are immersed all the time. Therefore it is necessary, instead of siphoning, to remove the beaker containing the electrolyte and replace it in a split second with a beaker of distilled water. No copper appears to be dissolved during this operation. The losses caused by spraying are small, and negligible as far as copper is concerned, since nearly all the copper is deposited in the first few minutes. No funnel was used to guard against spraying. Actually, although this method proved adequate for our needs, it was not suitable for obtaining extremely precise copper determinations.

Sometimes the copper deposit was black. This was probably caused by the presence of large amounts of iron in the solution, because, on dissolving and electrolyzing again in a pure dilute solution, red copper was obtained in virtually the same amount as previously.

After dissolving the electrolytically precipitated copper and washing the cathode, the resulting solution was boiled to expel nitrous compounds. Then water and sodium acetate were added, and copper was titrated after adding potassium iodide with a $\frac{N}{5}$ thiosulphate solution, using the microburette described by Hybinette and Benedetti Pichler (1942). This microburette, easily constructed in our laboratory, consists of a horizontal capillary glass tube with no stop-cock.

Dithizone extraction.—Fischer (1934) has shown that dithizone (diphenylthiocarbazone), dissolved in carbon tetrachloride or chloroform, can form, with a number of heavy metals, complexes soluble only in the organic solvent. Actually carbon tetrachloride is generally preferred to chloroform which is more toxic and has no definite advantages. As the carbon tetrachloride and chloroform are insoluble in water these heavy metals can be extracted in a water-insoluble layer even if these metals are present in minute amounts.

Dithizone is an intense green, and a solution containing 60 milligrams per liter appears deeply colored when viewed in an ordinary burette. The metal complexes are commonly red to purple, and this fact, taken in conjunction with the ability of the dithizone to extract virtually all the metal from a solution, is of practical value. The colors of the solvent and the complex are complementary in the physiological sense; consequently a suitable excess of dithizone will turn the color of the organic solvent layer, usually carbon tetrachloride, to neutral gray; with less dithizone it remains purple, and with more it turns green. Thus a "mixed color titration method" can be used to estimate the amounts of heavy metals in a solution. Grubitsch and Sinigoj (1938) claimed that accuracy within 2 to 3 per cent could be obtained with this method. Our own experience with different operators is that accuracy within 5 per cent may be obtained without difficulty by people with normal color vision.

A colleague, C. H. Howatson, used this extraction method. He shook the copper

solution with suitable amounts of the dithizone reagent in a separating funnel and gathered the saturated dithizone. This was separated until a nonpurple color indicated complete extraction of the metal. Dilute ammonia rid this last solution of all excess dithizone. Thus all the copper could be transformed and collected as dithizone complex. The whole complex was then measured in a graduated cylinder, and the concentration of this complex estimated by photocolorimetry.

Although this method may be as accurate, or even more accurate, than any other, we abandoned it because it was slow and cumbersome in the laboratory and not readily adaptable for field use.

Dithizone titration with "mixed color end point".—This method uses a general volumetric procedure; the dithizone solution from a burette is shaken with the metal-bearing solution in a measuring cylinder of 50-ml capacity provided with an emery stopper.

Of course the burette stopcock must not be lubricated with grease as the carbon tetrachloride would dissolve it and would leak out. For this lubrication glycerine may be used, preferably thickened with some animal glue. There are two methods of estimating the end point: (1) change from purple to a darker purple when dithizone is added in slight excess, and (2) change from purple to a neutral gray when a great excess of dithizone is added. The mixture must be vigorously shaken after each addition of dithizone, and with an excess of dithizone 2 minutes is a minimum for total extraction.

Method (1) was thoroughly tested as less reagent is needed. It is virtually as precise but requires better color appreciation. However, this method is somewhat slow, as the saturation point must not be passed, and thorough shaking is necessary after each addition of reagent as the end point is approached.

Method (2) is ideal for speed. As long as the color of the dithizone complex remains pure purple the minimum amount of dithizone needed to make the complex gray can be judged from the volume of the colored carbon tetrachloride layer. For copper this amount is about half the volume of this layer. As the end point is approached, it is not a matter of extracting minute amounts of copper left in a solution, but of adding enough dithizone reagent to change the color of the metal complex which has already been extracted.

Dithizone is not specific for copper, but, besides copper, only thallium and lead and precious metals form dithizone complexes from acid solutions stronger than pH4, and an abnormal amount of any of these metals is of as much interest to prospectors as copper. Mercury is evaporated, and any tin present is oxidized in the ashing and dissolution process; consequently they will not be present in a form in which they can react with dithizone. Nevertheless, in any investigations in a new area it is advisable to check any high copper determinations by the electrolytic method. With very dilute copper solutions—1γ per ml—some copper can remain partly unextracted. Consequently for samples containing normal amounts of copper one should use the ash from 3 grams of twig or at least 10 grams of wood in 20 ml of solution or less.

Of the methods investigated this dithizone titration with neutral mixed color end point seemed most promising, and it was used for the bulk of our final determinations. Further work will probably result in improved technique and especially in quicker

methods. This method can be used in the field, and analyses of satisfactory accuracy can be carried out in any reasonably well supplied base camp.

PROCEDURE

Ashes of 1 gram of plant material are dissolved in a few c.c. of 2N hydrochloric acid in a small beaker or in a 50 c.c. graduated cylinder which is heated to 60°–80° C in a hot water bath. There is no need for filtration; the insoluble material has no influence. Any manganese trichloride in the solution must be destroyed, otherwise the dithizone copper complex will be oxidized and turn yellow; this can best be accomplished by adding from time to time a drop of sulphur dioxide solution free from heavy metals. When the solution becomes practically colorless, with clear white particles of silica in suspension, add distilled water, which has been dithizone tested, to make an exact known volume between 10 and 30 ml; the whole solution at this stage must not contain over 3 per cent of hydrochloric acid. Then add from a burette a 60-milligrams-per-liter dithizone solution in carbon tetrachloride, shaking after each addition of this solution for 20 to 30 seconds, until the carbon tetrachloride layer is neutral gray. Zinc may be estimated from an aliquot part after copper has been extracted.

The dithizone solution may be standardized by using a solution of 100 γ copper per liter, about N acid, kept in a pyrex glass bottle, and diluted each time before using. This procedure is necessary because a very dilute solution will lose copper ions which can be absorbed on the walls of a flask within a few days or less.

It was not convenient to add progressive amounts of ash solution to the dithizone solution. The precision of the method is not increased, and the necessity for filtration makes it more cumbersome. In practice a 50-ml burette shortened to 20 ml proved satisfactory.

ZINC

Ferrocyanide (Zinc precipitation as sulphide and microtitration).—Hibbard (1934) devised the method we used for determining normal and subnormal amounts of zinc in plants. The ash is treated by 2N·HCl, and the solution buffered with ammonium citrate to pH3 and then treated with H_2S gas. Zinc is separated from this sulphide precipitate by dissolving it on the filter with cold N·HCl. The zinc is then determined by the classic ferrocyanide-iodide-thiosulphate method. In checking known amounts the results did not appear as satisfactory as those obtained in copper determinations, some results being more than 10 per cent both above and below the average. However, since our careful testing with dithizone showed that no zinc was being lost, we consider this method the most satisfactory we have tried. If carefully employed, it is specific for zinc, and we have used it to check the dithizone methods.

Zinc can be precipitated fairly accurately by 8-oxyquinoleine in acid solutions, down to amounts as low as 25 γ in 5 ml, corresponding to 5 p.p.m. in a 5-gram sample. However, in the presence of iron and aluminum, both of which occur in relatively large amounts in plant material, a further separation in an alkaline solution is needed. Our results indicated that some of the conclusions in the literature are probably overop-

timistic. We found that, using the same apparatus and method which worked successfully with acid solutions, as much as 0.1 milligram of zinc passed unprecipitated in 5 ml of alkaline solution.

Dithizone methods (as for copper but with a different pH).—Dithizone extracts zinc as it does copper, but from solutions less acid than pH4. As manganese gives a similar complex in neutral solutions some acidity must be retained. In practice a 10 per cent acetate solution was added in amount equal to, or even double, the volume of the $\frac{N}{2}$ to $\frac{N}{10}$ solution from which the copper had been extracted.

The remainder of the procedure is much the same as that for copper. However, it is inadvisable to shake strongly until the end point is approached, as the surface tension of the aqueous solution is lowered by acetate and the two liquids separate more slowly. Furthermore, the zinc is extracted more quickly than copper. The purple color is purer, and the neutral gray corresponds to an excess of dithizone approximately equal to the amount engaged in the zinc complex.

When in doubt over an abnormally high zinc determination one can make sure no manganese is involved by shaking the dithizone layer with a few milliliters of 10 per cent sodium acetate solution to which a few drops of acetic acid are added. Any manganese complex is decomposed, but the color of the zinc complex is unaffected. If any metal is removed the carbon tetrachloride layer turns from gray to green because of an excess of dithizone. In samples containing enough zinc to necessitate dilution in a volumetric flask, the excess of acid also becomes diluted, and the slightly acid buffer should be used instead of plain 10 per cent acetate.

SAMPLING

GENERAL

We realized early that sampling was important. When we were exploring the whole field, we tended to rely on large samples—around 500 grams—so that different analysts could try different methods of analysis on the same sample. However, it became apparent that a sample taken at random from a bag of ground material, even though it had been carefully mixed, might vary from another sample taken from the same bag under similar conditions, because the powdered material contains particles of different sizes and different metallic contents. Hibbard (1934) assumed that the smaller particles tended to be richest. We have not attempted to verify this assumption, but our experience suggests that samples taken at random may show variations far greater than any normal analytical errors.

Obviously, if the biogeochemical work were to have a field application it would not be possible to use such facilities as a Wiley mill; furthermore it would be inconvenient to wait for samples to dry, as they must before they are fit for milling. Consequently the use of large samples was stopped for field investigations. Large samples will still be necessary for control work and for complete analyses.

In selecting the portion of a tree or lesser plant for analysis it was important to consider: (1) was the part selected representative of the average content of metal which was being investigated; (2) could it be easily collected, transported, and treated in the field?

In our early work we found that the fruit and green portions usually contained the richest concentrations of metals. Unfortunately these parts did not prove to be as satisfactory samples as earlier work had led us to hope. Cones in particular were frequently either not available or not easy to obtain. The cones and the leaves and needles ashed to a fluffy product and varied in metal content. Our early work also indicated that the wood and dead bark of trees were unsatisfactory for biogeochemical investigations of copper and zinc, at least. We therefore investigated the metal content of young twigs. Table 1 shows the results of this investigation.

In Table 1, we observe that:

(1) The copper and zinc content of fruits, buds, leaves, and needles which are especially rich in living tissues is not on the average markedly superior to that of twigs, which are much poorer in living tissue.

(2) Twigs from 1 to 3 years old contain copper and zinc in amounts nearer the average for a bough than do other organs.

(3) Bark with young wood of the year adhering contains more copper and zinc per unit of dry material than does older wood—the bark and green wood contain more ash.

(4) Old wood has a low mineral content.

(5) Green material appears to show greater variation in copper and zinc content than do the other parts of trees and lesser plants.

Thus it would seem desirable to strip the bark from growing twigs and use this material for ashing. Actually, however, this bark is more bulky than the whole twig and produces a fluffy ash.

In practice it seems satisfactory to take twigs stripped of all leaves or needles and varying in thickness from one-eighth to one-fourth inch in diameter. One gram of small pieces cut from these twigs is representative enough for analysis.

COLLECTION OF SAMPLES

Previous work had satisfied the authors that the copper and zinc content of plants varies and that these variations could, in some areas at least, be correlated with the presence or absence of ore in the vicinity. However, many other factors also influence the copper and zinc content of plants, such as; (1) species of tree or lesser plant, (2) portion of tree or lesser plant selected for sample, (3) age of tree or lesser plant, (4) season at which sample taken, (5) pH of soil or material surrounding the roots of the plant, (6) topography of the area, (7) underlying country rock, (8) rainfall of the area, and (9) depth and nature of the overburden.

To eliminate at least some of these variables, the following method of sampling was adopted:

(1) Whenever possible, only one or two species were selected for sampling in any one area.

(2) The samples of conifers consisted of needles, small twigs, and cones from the top of trees; those of deciduous trees consisted of leaves stripped from a whole tree, as in most places the trees were small, and it proved difficult to get enough leaves for the large samples which at that time we thought necessary.

TABLE 1.—*Variations in copper content within boughs*

All these samples, unless otherwise noted, were selected from positive areas (copper) at Britannia.

SAMPLE NO.	DESCRIPTION	PER CENT ASH IN DRY MATERIAL	Cu:Zn	P.P.M. IN DRY MATERIAL	
				Cu	Zn
71	Tsuga heterophylla				
	—young needles	2	1.6	14	9
	—twigs bearing these needles	2.2	2	130	65
	Average for the bough	2	1.8	38	21
72	Alnus sitchensis				
	—leaves	2.9	1.1	131	117
	—buds	2.5	1.3	37	29
	—bare twig	2.7	0.74	69	93
	—fruits	1.6	0.9	30	34
	Average for the bough	2.5	1	90	90
73	Pseudotsuga taxifolia—				
	—(a) very young needles, with the twigs bearing them	1.1	1	7	7
	— older needles just below these	1.1	2	14	7
	— twigs bearing these needles	1.2	1.8	23	12
	— still older needles	0.7	0.4	2	5
	— twigs bearing these needles	1.3	1.1	13	12
	Average for the bough	1	1.3	9	7
	—(b) bark of a twig 6″ long from a bough 1′ long in all	1.3	1	24	25
	— old wood (the year's wood goes with the bark)	0.1	1	4	4
	Average for the twig	0.7	1	11	12
74	Abies amabilis—				
	—(a) young needles and twigs bearing them	1.2	3.0	38	13
	— older needles	1.1	0.5	3	6
	— twigs bearing these needles	1.4	1.2	30	24
	Average for the bough	1.2	1.8	20	11
	—(b) bark, including year's wood of a twig	1.6	1.1	26	23
	— old wood of this twig	0.4	1	4	4
	Average for the twig	1	1.1	16	14
75	Vaccinium ovalifolium				
	—leaves	5.7	<0.05	†	23
	—twigs	1.3	0.2	4	20
	Average for the bough	2.4	0.13	3	22
77	Tsuga heterophylla over staff house (negative)—				
	—end of twigs	1.6	0.2	9	43
	—needles	2.2	0.06	1	15
	Average for the bough	2	0.13	2	15

* Here and throughout the paper the Zn:Cu and Cu:Zn ratios are calculated, not directly from the copper and zinc contents as expressed in p.p.m. in the tables, but from the absolute amounts of Cu and Zn extracted from the sample during the making of the analyses.

† Less than one-millionth of the dry material.

(3) In each area only groups of trees of approximately the same age were sampled, and all samples were taken within a relatively short time.

(4) The samples for any group were taken from a relatively small area, in which, as

far as was possible, the slope, drainage conditions, and pH of the soil would be the same. Therefore the sample numbers are in groups on the maps.

About 300 grams of plant material were gathered for each sample, which was packed in a paper bag. At Kimberley the samples dried in air for about a week before they were packed in double paper bags and shipped to Vancouver. The samples from Britannia were packed and shipped within a week. There they dried for a month with the other samples.

PREPARATION OF SAMPLES FOR ANALYSES

The dried samples were ground in a Wiley Mill no. 1 to −40 mesh. The sieve was brass and may have contaminated the specimens. However, probably all specimens are contaminated to approximately the same degree, and our general results have apparently not been affected adversely. Actually, half of the Sullivan samples contained four parts per million or less of copper. Obviously salting from this source is negligible. The mill was cleaned thoroughly with a stiff brush after each sample had been ground. A few samples with high resin content left a sticky residue around the knives and in the grinding chamber, necessitating washing the grinding chamber and rotary cutter with xylene or spirits of turpentine. The samples were then analyzed.

Owing to the bulkiness of the samples, the drying time, and the need for a Wiley Mill or similar equipment to prepare them for ashing, we believe that this method of collecting and sampling is impracticable for prospecting and economical applications. However, these methods will be useful when controls are being set up in a new area or when complete analyses of plant material are needed.

SELECTION OF AREAS

In choosing areas for study it was advisable to select those known to contain copper or zinc ore bodies of economic importance and which had been thoroughly studied geologically. Furthermore, the ore bodies should be undergoing oxidation. Limited funds added another restriction-accessibility. Fortunately, two of the areas already studied, the Sullivan and Britannia mines, filled these requirements, and our preliminary conclusions, arrived at by studying these areas, provided data which indicated what metal content we might expect in trees adjacent to and removed from buried bodies of ore.

STUDIES OF INDIVIDUAL AREAS

SULLIVAN (KIMBERLEY) AREA

General.—Our previous papers refer to this area as Chapman Camp. However, as the Sullivan mine is world famous, we now refer to it as the Sullivan rather than as the Chapman Camp area. The Sullivan, one of the great lead, zinc, and silver mines of the world, is in southeastern British Columbia about 20 miles northwest of the town of Cranbrook.

Swanson and Gunning (1944) present a timely background for biogeochemical studies. The general geology given here is abstracted or quoted from that publication.

Climate.—The Sullivan area has a typical "interior" climate: a relatively dry atmosphere with cold winters and hot summers. Our work was done in an area 4000 to 5000 feet above sea level. Precipitation averages 25 to 30 inches a year, including 6 to 15 inches in snowfall. Our collecting was done during late June and early July 1946.

General geology.—"The deposit is essentially a sulphide replacement of certain beds which form a stratigraphic zone 200 to 300 feet thick in the Aldridge formation." The Aldridge is an upper pre-Cambrian sedimentary formation composed of argillite, siltstone, and quartzite. It has been altered considerably in the vicinity of the ore bodies; chlorite and albite rock are conspicuous in the hanging wall, and tourmaline rock on the footwall. This tourmaline may be important in biogeochemical investigations as it contains boron, and element now generally recognized as essential to plant growth.

Two areas of diorite and associated granophyric rock are also mapped. The foot wall of the ore zone does not carry on "commercially" through these rocks, and the zinc content of the plants over these rocks is noticeably below that of plants over, or topographically below, the footwall of the ore zone.

The principal sulphides include galena and sphalerite. Chalcopyrite occurs in the ore but is quantitatively negligible.

The Sullivan, East, and Lois faults postdate the ore; consequently any area where the plane of any of these faults intersects the plane of the footwall of the ore zone in the vicinity of the surface provides a useful place to test the metal content of the near-by trees.

Sampling.—With this idea in mind several groups of samples were taken. Plate 1 shows the location of each sample.

Group 1. Close to the Sullivan No. 1 fault and near the outcrop of the footwall in the Aldridge formation.

Group 2. Close to the Sullivan No. 1 fault but in the diorite and granophyric rocks. Sample No. 51 is placed here as it is in the igneous rock. However, it comes from near the edge of these rocks and is relatively close to the footwall outcrop.

Group 3. In the Aldridge formation near no major fault but varying from 500 feet below the outcrop of the footwall of the ore zone to immediately above it.

Group 4. (a and b) Within approximately 600 feet of the intersection of the East Fault and the footwall of the ore zone, all in the Aldridge formation.

Group 5. Within 500 feet of the Lois fault, but 300 feet or more from the indicated termination of the footwall of the ore zone, all in the diorite and granophyric rocks.

Unfortunately the depth of overburden is not known everywhere, but it is indicated where known (Pl. 1).

All the samples were taken from areas known to be positive. The possibility of salting caused considerable worry, but all the negative samples taken during our preliminary investigations were low in zinc relative to their corresponding positive samples.

Any initial reader will ask why we did not take more samples away from the trace of the ore zone. The reasons for this were (1) our preliminary work had indicated an average zinc content in positive areas of about 100 to 120 p.p.m. of dried plant ma-

terial, and in negative areas of between 30 and 40 p.p.m.; (2) we were always trying to cut costs, and when sampling had to be eliminated we elected to omit negative specimens. Actually our results fitted in with those obtained in our preliminary investigations, always remembering that we deliberately had two different collectors and two different analysts.

Copper and zinc.—Table 2 summarizes the copper and zinc results obtained from the Sullivan mine. The analyses reported are all from the dithizone gray color end point method.

Boron content of some trees.—Knowing that the Sullivan ore was close to much tourmalinized chert and that boron is important in plant nutrition, we investigated the boron content of some positive and negative samples from this area. The work was exploratory, and consequently no serious attempt was made to obtain quantitative results. However, chiefly on the basis of the comparative strength of particular boron lines, actually the 2497Å and 2498Å, a distinction was made on the amount of boron present. The boron was recorded as absent or trace, weak, medium, or strong, a recording with no absolute value, but reasonably sound for comparative purposes. The determinations were recorded on 2- by 10-inch Eastman type II F. (Tropical) plates, which have a useful range between 2200 and 6800 Å, from arc excitation through a medium Hilger quartz spectroscope. Each "shot" consisted of impressing on a plate, with a Hartmann diaphragm, a series of tangent narrow strips constituting the successive spectra of (1) the ash sample arced for 10 seconds, (2) the ash sample arced for 20 seconds, (3) the iron arc (from Hilger's "spec pure" iron rods). To check on the purity of the carbons and to insure against electrode contamination, every plate negative had impressed on it a spectrum of the empty carbon electrodes. A wave-length scale was also reproduced with each "shot", and this scale, together with the iron spectra, made it possible to measure the lines with considerable accuracy.

In relatively crude work of this type the judgment of the operator must be considered. A senior student learning technique on a medium Hilger spectroscope was given 25 samples of ashed plant material and asked to report on the boron content of each sample which was known to him only as a number. Nine of these samples were from the Sullivan area—five from negative, and four from positive areas (Table 3).

These data suggest that in this area it would be interesting to investigate the relationship between the boron content of trees and the zone where the footwall of the ore zone approached the surface.

Manganese in samples from the Sullivan area.—Recent spectrographic examinations (Warren and Thompson, 1945) show that the sphalerite from the Sullivan mine is much richer in manganese than are any other sphalerite occurrences in British Columbia. Manganese, like zinc, copper, and boron, is important in plant growth. The Sullivan area, therefore, seemed to be one which might provide some parallel between the zinc and manganese content of plants in positive and negative zinc areas, particularly as the host rocks of the ore bodies are not known to contain any appreciable amounts of manganese. Suites from both positive and negative areas were collected (Warren and Howatson, 1947). The results were as shown in Table 4; the manganese is expressed in p.p.m. of dried plant material.

TABLE 2.—*Summary of copper and zinc from the Sullivan mine*

SAMPLE NO.	SPECIES	METAL CONTENT IN P.P.M. OF AIR-DRIED PLANT MATERIAL		Zn:Cu
		Cu	Zn	
	GROUP 1			
54	Pinus contorta (Lodgepole pine)	4	57	13
56		3	60	20
57		3	48	12
58		4	46	10
60		5	86	16
	Total	20	297	
	Average	4	60	15
55	Salix sp. (Willow)	13	210	16
59		12	240	20
	Total	25	450	
	Average	12	225	18
	GROUP 2			
3	Lodgepole pine	5	80	17
51		2	100	65
	Total	7	180	
	Average	3	90	26
4	Willow	14	540	40
5	Alnus sinuata (?) (Green alder)	8	74	9
	GROUP 3			
1	Lodgepole pine	5	360	130
6		6	100	18
15		4	90	20
18		3	200	65
20		5	140	30
50		4	220	50
52		5	170	36
53		4	280	64
	Total	36	1560	
	Average	4	195	43
2	Willow	12	300	24
14		12	460	38
19		2	460	230
21		8	640	150
	Total	34	1860	
	Average	9	460	55

TABLE 2.—(*Continued*)

SAMPLE NO.	SPECIES	METAL CONTENT IN P.P.M. OF AIR-DRIED PLANT MATERIAL		Zn:Cu
		Cu	Zn	
	GROUP 4(a) (More than 150 feet from East fault)			
7	Lodgepole pine	5	160	35
8		4	200	50
10		13	200	16
12		6	86	16
16		3	40	14
22		4	90	20
25		5	160	35
26		4	110	28
28		5	160	33
43		4	54	13
	Total	53	1260	
	Average	5	126	24
9	Willow	8	800	100
11		9	900	100
13		11	370	35
17		7	160	23
23		6	380	63
24		2	1100	550
27		9	740	80
29		8	860	110
42		5	170	30
	Total	65	5480	
	Average	7	609	90
	GROUP 4(b) (Within 100 feet of East fault)			
30	Lodgepole pine	4	140	33
33		4	640	170
34		3	200	70
35		4	220	60
37		5	500	100
39		5	170	37
41		3	76	27
	Total	28	1946	
	Average	4	280	70
31	Willow	6	1000	170
32		8	860	110
36		9	800	90
38		9	500	53
40		7	500	70
	Total	39	3660	
	Average	8	732	90

TABLE 2.—(*Concluded*)

SAMPLE NO.	SPECIES	METAL CONTENT IN P.P.M. OF AIR-DRIED PLANT MATERIAL		Zn:Cu
		Cu	Zn	
	GROUP 5 (Vicinity of Lois Fault)			
44	Lodgepole pine	3	60	18
45		4	54	15
47		4	28	7
48		3	74	23
49		3	60	20
	Total	17	276	
	Average	3	55	16
46	Picea (?) (Spruce)	6	90	15

SUMMARY

	NUMBER OF SAMPLES		METAL CONTENT IN P.P.M. OF AIR-DRIED PLANT MATERIAL		
			Cu	Zn	Zn:Cu
Group 1	Lodgepole pine	5	4	60	15
2		2	3	90	26
3		8	4	195	43
4(a)		10	5	126	24
4(b)		7	4	280	70
5		5	3	55	16
Group 1	Willow	2	12	225	18
2		1	14	540	40
3		4	9	460	55
4(a)		9	7	609	90
4(b)		5	8	732	90
5		—	—	—	—

Specimens of Table 4 show interesting differences. The average manganese content is somewhat less than half that of zinc; and the manganese, on the basis of a limited number of samples, appears to be differently distributed in the plant organs. There seems to be relatively more manganese in wood and bark than there is zinc, and the two samples of fruit contain (relatively) little manganese.

Comparison with previous results.—These results cannot be directly compared with those previously obtained. In our earlier work we were exploring many possibilities, including the metal content of different organs and of different trees and lesser plants. In addition, our results were reported in p.p.m. of ash in contrast to our present

method of giving the content in p.p.m. of dried plant material. Nevertheless, the results are complementary and certainly are not antagonistic.

In our preliminary work in this area we found that in the positive areas the plants

TABLE 3.—*Boron in trees from Sullivan area*

(Optical Spectroscopy)

SAMPLE NO.	POSITIVE OR NEGATIVE	SPECIES	ORGAN	BORON CONTENT
166	−	Larix occidentalis (Larch)	bark	absent or trace
167	−	Shepherdia canadensis (Soopolallie)	leaves	medium
175	−	Pinus contorta (Lodgepole pine)	cones	absent or trace
180	−	Populus trichocarpa (Black cottonwood)	leaves	weak
182	−	Populus tremuloides (Aspen)	leaves	weak
151	+	Larch	cones	strong
155	+	Black cottonwood	leaves	strong
163	+	Soopolallie	leaves	strong
165	+	Salix sp. (Willow)	leaves	strong

TABLE 4.—*Manganese in trees from Sullivan area*

		POSITIVE	NEGATIVE
Pinus contorta (Lodgepole pine)	—cones	3	3
" "	—bark	68	27
Populus trichocarpa (Black cottonwood)	—leaves	83	2
" "	—wood	29	9
Salix sp. (Willow)	—leaves	289	no sample taken
"	—bark	60	9
Larix occidentalis (Larch)	—leaves	101	7
" "	—cones	6	no sample taken
" "	—bark	82	33
Populus tremuloides (Aspen)	—leaves	75	7
" "	—bark	39	no sample taken
" "	—wood	12	no sample taken
Shepherdia canadensis (Soopolallie)	—leaves	2	5
Total		849	102
Average		65	12

contained over 100 p.p.m. of zinc in dried plant material, as against 30 to 40 in the negative areas. In Table 2, which represent collections of positive samples from different distances from the ore deposits, our preliminary figures have been amply confirmed. Furthermore, we can now say that evidence of mineralization below the surface can be noted for distances up to 300 feet from the source, and through at least 30 feet of overburden. Deciduous trees also proved to be better indicators of metals than are the evergreens. However, the zinc to copper ratio seems to be a more important guide to the presence of zinc ore than does even the absolute amount of zinc

in plant material. This, of course, may be expected only where the zinc ore does not carry significant amounts of copper.

BRITANNIA MINE AREA

General.—This area lies about 20 miles due north of Vancouver in a typically rugged section of the Coast Range mountains of British Columbia. Near the mine uninterrupted slopes rise from sea level to elevations of 4500 feet within a horizontal distance of less than 1½ miles.

Samples were collected from two localities: from the vicinity of two veins known to occur near the surface about 4000 feet above sea level, and from an area contiguous to the copper plant. Water from the mine is passed over scrap iron on which the copper is precipitated. We have referred to buildings where this precipitation takes place as the copper plant. This plant is unrelated to any mill or concentrator, and is situated at the Tunnel Camp not far from the main portal of the mine at an elevation of 2100 feet above sea level.

Climate.—The climate is moderate. There is considerable variation because of the extreme relief. No figures are available for the actual precipitation at higher levels where, at elevations of 3000 to 4000 feet, the snow may be measured in tens of feet, and where it remains on the ground for several months. Probably well over 60 inches per year falls in the two areas where the samples were taken. Our collections were made in late August and early September 1946 and in late August 1947.

General geology.—Virtually all the geological information in this report has been extracted from James' (1929) report on the Britannia mine.

Ore deposits at Britannia occur in the well-defined Britannia shear zone. The country rock is green-mottled schist composed essentially of chlorite and sericite. The Britannia mine consists of a number of ore bodies, each unique. Some of these ore bodies do not outcrop and hence were not investigated. The mine near which the first suite was collected is the Fairview mine. The ore occurs in a number of veins of which only two were studied. These veins—known at the mine as No. 9 and No. 11 veins—are near the hanging-wall portion of the Britannia shear zone, and each of them consists of a broad zone of commercial ore. They are separated from each other by bands of mineralized schist. These broad zones comprise a great number of narrow individual veinlets in which, aside from quartz which is the dominant mineral, pyrite and chalcopyrite are the only important minerals. Sphalerite is unimportant at the Fairview mine, so the samples taken from the vicinity of No. 9 and No. 11 veins may be considered as copper positive and zinc negative. Figure 4 shows the locations of the samples.

The second suite of Britannia samples is not associated with any particular mine at Britannia. A substantial amount of copper is recovered from mine waters at a copper precipitation plant, and a suite of samples was collected from the vicinity of this plant where it was realized there must be relatively high concentrations of copper in the ground water. However, these ground waters also contain much zinc, as many of the ore bodies, unlike those of the Fairview, contain considerable zinc—indeed, in places it is ore. This suite, referred to as the "Copper Plant Suite", is primarily copper positive, zinc positive. Actually the samples from north of Britannia Creek and

those from the higher ground northwest of the copper plant and between the draw carrying the overflow from the copper plant and Jane Creek are intermediate between positive and negative both for zinc and copper. It might be assumed that any trees

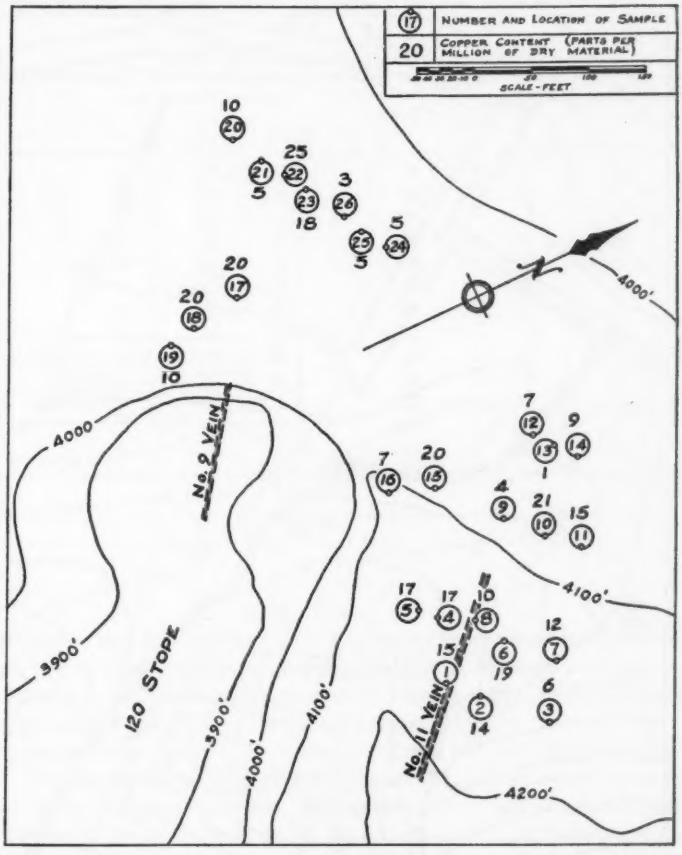


FIGURE 4.—*Map showing location of Fairview Mine samples, Britannia Beach, B. C.*

or lesser plants tapping water from Britannia Creek above the tunnel dam (Fig. 5), Jane Creek, or the overflow from the copper plant contain abnormal amounts of copper and zinc, but that these amounts will be less than those obtained from the immediate vicinity of the copper plant. Actually Figure 5 shows just how well such an assumption can be substantiated by actual field work.

Vogt and Bugge (1943) described willows apparently poisoned by lethal amounts of metal which, however, were probably no greater than are present close to the copper precipitation plant at Britannia. The poisoning may have resulted from some other chemical factor, such as soil acidity, rather than excess copper or iron. The water

from Britannia mine is neutralized in the recovery plant. This, and the fact that most of the water which escapes from the plant must pass through a wood-ash heap derived from copper-rich burned mine timbers used as fuel, insures the near-by

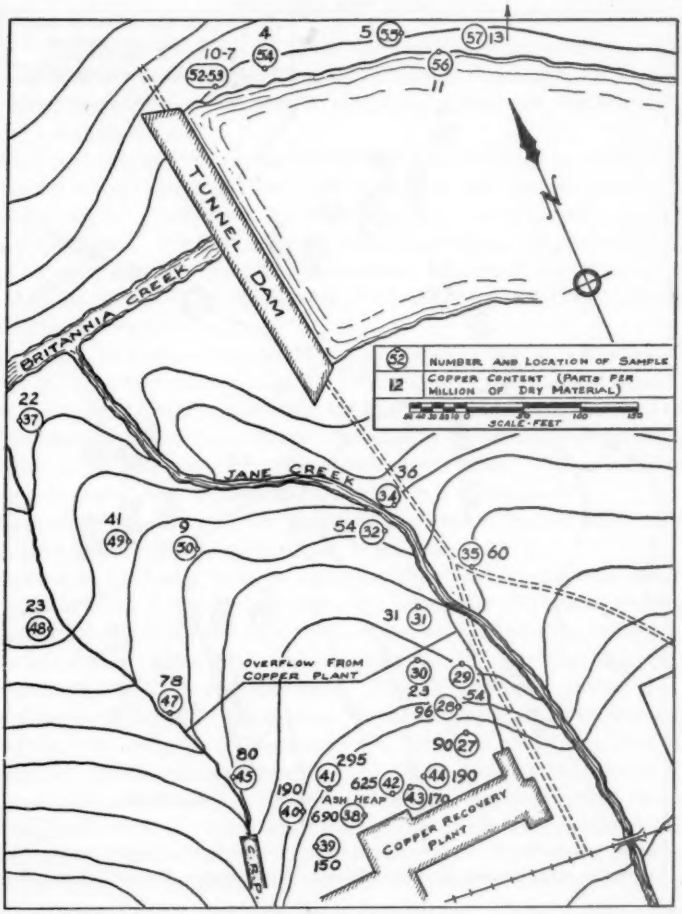


FIGURE 5.—*Map showing location of samples taken from the vicinity of the Copper Plant, Britannia Beach, B. C.*

trees a rich supply of copper without a lethal amount of acid. Except for one alder growing on the middle of the ash heap (ash from this tree contained 2 per cent copper, all the trees in the vicinity of the copper plant looked normal and healthy despite their high copper content.

Fairview No. 9 and No. 11 suite.—The analyses in Table 5 are of spruce (Picea sitchensis) trees of similar age and from localities indicated on Figure 4.

Copper plant suite.—The locations of the samples in Table 6 are indicated in Figure 5.

The only samples that contained more than 4 times as much zinc as copper (Samples 52, 53, 54, and 55) were from the north side of Britannia Creek where they were relatively removed from the copper-bearing solutions reaching the copper plant.

Comparison with previous results.—Earlier work at Britannia showed that in

TABLE 5.—*Fairview No. 9 and No. 10 suite*

SAMPLE NO.	P.P.M. OF DRIED MATERIAL			SAMPLE NO.	P.P.M. OF DRIED MATERIAL		
	Cu	Zn	Cu:Zn		Cu	Zn	Cu:Zn
1	15	28	0.5	14	9	31	0.3
2	14	31	0.5	15	20	32	0.6
3	6	32	0.2	16	7	35	0.2
4	17	32	0.5	17	20	26	0.8
5	17	83	0.2	18	20	23	0.9
6	19	26	0.7	19	10	28	0.4
7	16	32	0.5	20	10	36	0.3
8	10	24	0.4	21	5	30	0.16
9	4	10	0.4	22	25	27	0.9
10	21	49	0.4	23	18	26	0.7
11	15	13	1.2	24	5	35	0.14
12	7	26	0.3	25	5	34	0.15
13	1	20	0.05	26	3	28	0.11

NO. 1 TO 26	Cu	Zn
Total	319	797
Average	12	30

selected areas at least the copper content of trees and lesser plants from positive areas was much greater than that from negative areas. Also, the amount of copper in the trees and lesser plants from negative areas in the vicinityof Britannia consistently was higher than appears "normal" in the light of present evidence.

Furthermore, in our earlier collections, we included not only the fruit of mountain hemlock, but also the leaves of one or two species of plants now considered to carry abnormally high amounts of copper. If, however, these factors are all considered, there is a remarkable parallelism between the present results and those in our previous paper. This parallelism is all the more significant because one man collected and another analyzed, and the analyst was given no clue as to the origin of the sample except that in the latest work, to expedite analytical processes, the analyst was advised of samples which might be high in zinc or copper.

CONCLUSIONS

In our previous work we found the zinc and copper content of the organs of some trees and lesser plants to be as much as 1000 p.p.m. However, Vogt and Braadlie (1942) found over 500 p.p.m. of copper in Melandrium dioicum, and Robinson, Lakin, and Reichen (1947) found well over 4000 p.p.m. of zinc in Linaria vulgaris, Equisetum arvense, Lobelia inflata, and Achillea millefolium L. It seems reasonable to assume

TABLE 6.—*Copper plant suite*

SAMPLE NO.	NAME	P.P.M. OF DRIED MATERIAL		
		Cu	Zn	Cu:Zn
	GROUP 1 within 150 feet of Copper Plant			
27	Tsuga heterophylla (Western hemlock)	90	200	0.4
28		96	198	0.4
29		54	37	1.5
30		23	23	1
38		690	1300	0.5
39		150	93	1.5
40		190	120	1.6
41		295	180	1.6
44		190	110	1.8
45		80	74	1.1
	Total	1858	2335	0.8
	Average	186	233	
42	Alnus rubra (Red alder)	625	255	2.5
43		170	310	0.5
	Total	795	565	1.4
	Average	400	280	
	GROUP (2) more than 150 feet from Copper Plant			
31	Tsuga heterophylla	31	32	1
32		54	33	1.6
33		42	51	0.7
34		36	49	0.7
35		60	58	1
36		22	23	1
37		22	52	0.4
46		110	110	1
47		78	45	1.7
48		23	53	0.4
49		41	32	1.3
50		9	32	0.3
51		9	20	0.4
54		4	59	0.07
55		5	64	0.08
56		11	35	0.3
57		13	34	0.4
	Total	570	792	0.7
	Average	34	47	
52	Pseudotsuga taxifolia (Douglas fir)	10	68	0.15
53	Alnus rubra (Red alder)	7	94	0.07

that the pH of the soil is a more important factor than either the zinc or copper content of the ground water in determining the amount of zinc or copper which may be toxic to trees and lesser plants.

One of our earlier conclusions must be altered. We stated that in the average zinc was twice as abundant as copper. On the basis of present evidence, at least in the areas investigated, zinc is nearly ten times as abundant in the living organs of trees and lesser plants.

A study of the zinc-copper ratio in all the samples investigated suggests that it is much more important in biogeochemical prospecting than is the absolute amount of these metals. The tabulated copper-zinc ratios admittedly prove nothing, but they, together with the Sullivan and Britannia analyses, suggest most strongly that: (1) the copper-zinc ratio in the various organs is far more uniform than are the absolute values of either copper or zinc; (2) the "normal" copper-zinc ratio is probably in the range of .10 to .15; (3) a copper-zinc ratio of over .15 in igneous or metamorphic areas suggests the presence of abnormal amounts of copper; (4) in an area of zinc concentration the zinc-copper ratio will rise from an average of about 10 to about 100, and to 500 at places devoid of copper ore.

Table 1 gives analyses of various organs in p.p.m. of copper and zinc and also the copper-zinc ratio. The copper-zinc ratio is relatively constant in comparison with the copper or zinc content of the organ concerned.

Thus, biogeochemical methods definitely offer a new tool in the search for drift-covered ore bodies.

REFERENCES CITED

Fischer, Hellmuth (1934) *Über die Anwendung von Dithizon* (*On the use of dithizone*), Zeitschr. Anal. Chem., vol. 96, p. 128.

——— and Leopoldi, G. (1936) *Nachweis und Bestimmung von kleiner Zinkmengen* (*Detection and determination of small amounts of zinc*), Zeitschr. Anal. Chem., vol. 107, p. 241.

Grubitsch, H., and Sinigoj, J. (1938) *Über die Genauigkeit der Dithizon Mischfarbentitration* (*On the accuracy of the mixed color titration of dithizone*), Zeitschr. Anal. Chem., vol. 114, p. 30.

Hawkes, H. E. (1946) *Geological Survey's geochemical prospecting unit*, Paper presented November 13 at meeting of Geological Society of Washington, p. 4.

Hibbard, P. L. (1934) *Micromethods for determination of zinc*, Ind. Eng. Chem. (Anal.), vol. 6, p. 423.

Hybinette, A. G., and Benedetti, Pichler, A. A. (1942) Mikrochemie ver. Mikrochim Acta 30, 15–22, see *Introduction to them icrotechnique of inorganic analysis*, John Wiley and Sons, New York.

James, H. T. (1929) *Britannia Beach map area British Columbia*, Geol. Survey Canada, Mem. 158.

Robinson, W. O., Lakin, H. W., and Reichen, Laura E. (1947) *The zinc content of plants of the Friedensville zinc slime ponds in relation to biogeochemical prospecting*, Econ. Geol., vol. 42, p. 572–582.

Swanson, C. O., and Gunning, H. C. (1944) *Geology of the Sullivan mine*, Western Miner, vol. 17, p. 74–94.

Vogt, Thorolf, and Braadlie, O. (1942) *Plantevekst og jordbunn ved Rørosmalmene* (*Vegetation and soil at the ore deposits at Røros*), D. K. Norske Videnskabers Selskab, Forhandlinger, vol. 15, no. 7, p. 25–28.

——— — Bugge, Jens (1943) *Bestemmelse av kobber i planter fra Rorosfeltet ved kvantitative rontgenanalyse* (*Determination of copper in plants from the Røros district by quantitative X-ray analysis*), D. K. Norske Videnskabers Selskab, Forhandlinger, vol. 16, no. 14, p. 51–54.

Warren, H. V., and Howatson, C. H. (1947) *Biogeochemical prospecting for copper and zinc*, Geol. Soc. Am., Bull., vol. 58, p. 803–920.

——— — Thompson, R. M. (1945) *Sphalerites from Western Canada*, Econ. Geol., vol. 40, p. 309–335.

TABLE A.—*Zinc in trees from Sullivan area by different chemical methods*

SAMPLE NO.	(A) GRAY COLOR END POINT 1 GRAM	(B) GRAY COLOR END POINT 5 GRAMS	(C) DARK PURPLE END POINT 1 GRAM	(D) FERROCYANIDES 1 GRAM
1	110	360	170	140
2	250	300	260	250
3	65	80	40	50
4	380	540	370	
5	80	74	310	
6	80	100	100	
7	150	160	104	100
8	200	200	225	350
9	150	800	400	
10	280	200	310	460
			220	
11	690	900	870	1240
			900	
12	110	100	120	100
13	47	370	100	180
14	190	460	650	880
15	110	90	120	150
16	60	40	125	70
17	170	160	170	150
18	130	200	225	90
			130	
19	400	460	600	520
			700	
20	480	140	250	280
21	480	640	700	580
			620	
22	110	90	125	165
23	270	380	340	325
24	650	1100	800	640
			650	
25	170	160	250	280
				240
26	110	110	145	
27	750	740	850	
28	100	160	170	
29	550	860	500	
30	120	140	130	
31	650	1000	570	

APPENDIX

Table A shows the results obtained in some zinc determinations using various analytical methods, all figures in p.p.m. of air-dried plant material. The dithizone gray color end-point method was tried on both 1- and 5-gram samples. Some results are much less precise than they should be. The 1- and 5-gram gray color end-point analyses were carried out on different sampling, by two analysts, at separate

times. Moreover the analyses were made under unsatisfactory conditions which would allow occasional salting. New laboratory accommodation should do much to remedy this difficulty. Apart from occasional differences which are entirely out of

TABLE B.—*Copper in trees from Sullivan Mine by different chemical methods*

SAMPLE NO.	DITHIZONE GRAY COLOR END POINT		ELECTROLYSIS 1 GRAM
	(a) 1 gram	(b) 5 grams	
1	1	5	6
			1
2	4	12	1
3	1	5	none
4	3	14	6
5	4	8	6
6	1	6	1.5
7	1	5	4
8	1	4	1
9	1	8	2
11	1	9	1
12	1	6	none
14	1	12	6
15	1	4	1
16	1	3	1
17	6	7	10
19	2	2	10
20	3	5	none
			1
21	6	8	12
23	4	6	9
24	10	2	15
26	1	4	none
31	5	6	2
39	1	5	none
41	1	3	1
46	1	not done	1
48	1	3	1
53	1	4	4

line, the zinc determinations on the 1-gram samples seem to be satisfactory; these are the results appearing on Plate 1, the preliminary drafting of which was being done when the 1-gram samples were being run. In the paper the 5-gram sample results are used because although high zinc contents can be readily determined on 1-gram samples, low copper contents can not. This latter fact we did not appreciate until relatively late in our experiments. By using the results from 5-gram samples from the Sullivan area our results conform much more satisfactorily than they did by using those of 1-gram; the latter were much too low in copper.

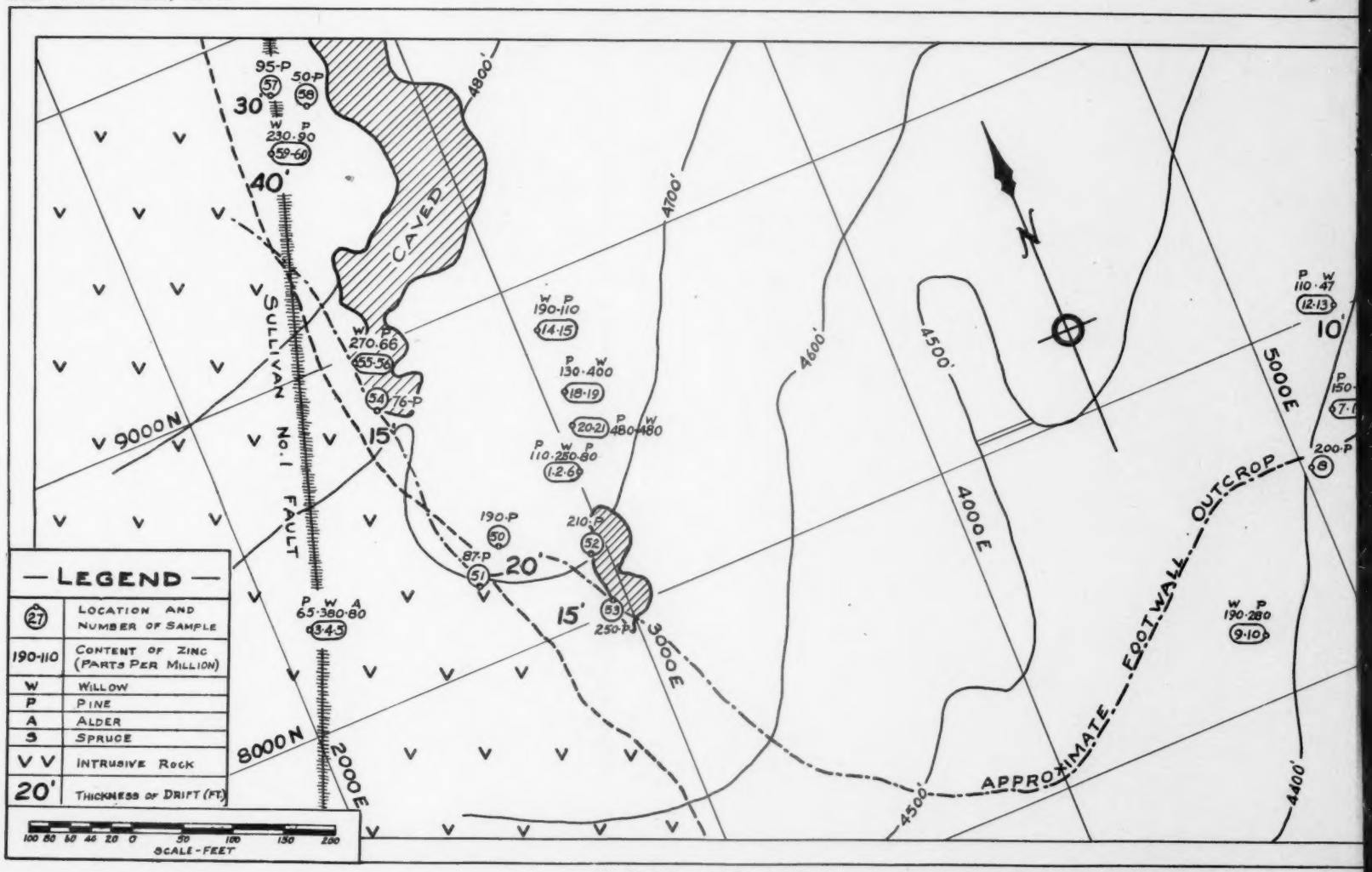
Table B gives the results of different copper analyses. It must again be emphasized that our electrolysis method is not specific for low copper determinations. It gives good results in analyses in which the copper content is more than 10 p.p.m.

TABLE C.—*Copper in trees from Britannia and Van Anda (Texada Island) by different chemical methods*

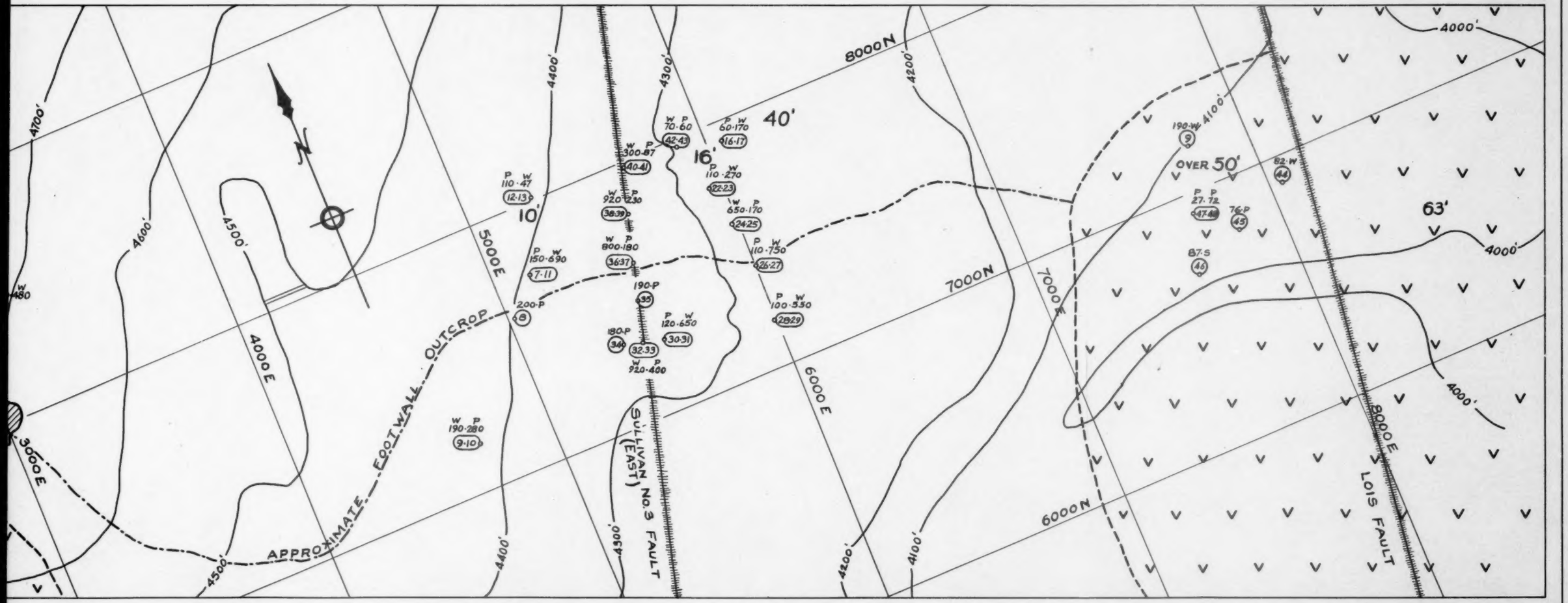
SAMPLE NO.	DITHIZONE (GRAY COLOR END POINT)	ELECTROLYSIS	SAMPLE NO.	DITHIZONE (GRAY COLOR END POINT)	ELECTROLYSIS
B. 1	15	18	B.42	625	536
B. 2	14	21	B.43*	170	11
B. 3	6	9		140	
B. 4	17	5	B.44	190	216
B. 5	17	9			114
B. 6	19	12	B.45	80	122
B. 7	16	12	B.47*	78	4
B. 8	10	6	B.48	23	7
B. 9	4	16	B.49	41	35
B.10	21	25	B.50	9	4
B.12	7	10	B.52	10	10
B.13	1	16	B.54	4	4
B.14	9	8	B.55	5	2
B.15	20	17	B.56	11	7
B.16	7	12	B.57	13	2
B.17	20	5	101	5	1
B.18	20	11	102	3	14
B.19	10	10	103	4	1
B.20	10	12	104	3	1
B.21	5	6	105	4	1
B.22	25	8	106	7	2
B.23	18	22	107	1	4
B.24	5	7	108	6	7
B.26	3	12	109	5	7
B.27	90	124	115	3	6
B.28	96	91	118	5	8
B.29	54	44	124	5	7
B.30*	8	78	128	2	1
B.31	31	8	130	3	1
B.32	54	25	135	3	1
B.33	42	39	139	2	5
B.34	36	5	141	4	2
B.35	60	29	144	4	1
B.36	22	14	148	2	1
B.37	22	8	150	2	none
B.38	690	600	155	4	1
B.39	150	104	158	3	8
B.40	190	173	160	2	none
B.41	295	186			
		168			

* No reason apparent for these variations. In each case the higher assay is thought to be correct.

Furthermore, even using the dithizone gray color end point method, it is not possible to get satisfactory results using only 1-gram samples if the copper content is low. Some of the low copper determinations have been rerun on 5-gram samples, and the results are given in Table B. Positive results of less than 1 p.p.m. are given as 1.



MAP SHOWING LOCATION OF SULLIVAN MI



MAP SHOWING LOCATION OF SULLIVAN MINE SAMPLES, KIMBERLY, BRITISH COLUMBIA

As with the zinc results, it is fair to assume that some of the more obvious discrepancies, such as B.39, B.43, B.47, are the result of salting and some are the result of our own ineptness. Neither the zinc nor the copper results suggest than an ideal method of analysis has been found. Nevertheless, if several analyses are averaged, reasonably consistent results are obtained.

University of British Columbia, Vancouver, Canada.
Manuscript Received by the Secretary of the Society, January 26, 1948.
Project Grant 449/46/5/47.